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Institute of Sports and Preventive Medicine

Pacing in Swimming – Variability and Effects of Manipulation

By

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Declaration

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Sabrina Skorski

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Abbreviations

ANOVA	Analysis of variance
Cl	Confidence limit
CV	Coefficient of variation
iEMG	Integrated surface electromyography
m	Meter
p	Significance level
PP	Pacing pattern
PP_{FAST}	Fast-start pacing pattern
PP_{SLOW}	Slow-start pacing pattern
PP_{SS}	Self-selected pacing pattern
RPE	Rating of perceived exertion
s	Second
SEM	Standard error of measurement
VO_2	Oxygen consumption
VO_{2max}	Maximum oxygen consumption
y	Years

Figures

List of Publications for the Thesis

1. Skorski S, Faude O, Rausch K, Meyer T. Reproducibility of Pacing Profiles in competitive Swimmers. *International Journal of Sports Medicine*. 2013 Feb;34(2):152 – 157.
2. Skorski S, Faude O, Caviezel S, Meyer T. Reproducibility of Pacing Profiles in Elite Swimmers. *International Journal of Sports Physiology and Performance*. 2014 Mar;9(2):217-225.
3. Skorski S, Faude O, Abbiss CR, Caviezel S, Wengert N, Meyer T. Influence of Pacing Manipulation on Performance of Juniors in Simulated 400 m Swim Competition. *International Journal of Sports Physiology and Performance*. 2014 Sep;9(5):817-824.

Further related publications not included in the thesis

1. Renfree A, Mytton, GH, Skorski S, St Clair Gibson A. Tactical Considerations in the Middle Distance Running Events at the 2012 Olympic Games. *International Journal of Sports Physiology and Performance*. 2014 Mar;9(2):362-364.
2. Skorski S, Hammes D, Schwindling S, Veith S, Ferrauti A, Kellmann M, Meyer T. Effects of Training-Induced Fatigue on Pacing Patterns in 40-km Cycling Time Trials. *Medicine and Science in Sport and Exercise*. 2014 July; (ePub ahead of print).
3. Mytton GJ, Archer DT, Turner L, Skorski S, Renfree A, Thompson KG, St Clair Gibson A. Increased Variability of Lap Speeds Differentiate Medallists and Non-Medallists in Middle Distance Running and Swimming Events. *International Journal of Sports Physiology and Performance*. 2014 Sep; (ePub ahead of print).
4. Skorski S, Etxebarria N, Thompson KG. Breaking the Myth: Relay Swimming is Faster than Individual Swimming. *International Journal of Sports Physiology and Performance*. (under review).
5. Abbiss CR, Peiffer JJ, Meeusen R, Skorski S. Effort vs. Exertion: Role of RPE during Self-Paced Exercise. *Sports Medicine*. (under review).

Abstract

Introduction: In any athletic event, the ability to appropriately distribute energy, is essential to prevent premature fatigue prior to the completion of the event. In sport science literature this is termed '*pacing'*. Within the past decade, research aiming to better understand the underlying mechanisms influencing the selection of an athlete's pacing during exercise has dramatically increased. It is suggested that pacing is a combination of anticipation, knowledge of the end-point, prior experience and sensory feedback. To date, most of this research has been conducted in running or cycling, with studies focusing on pacing in swimming currently lacking. This is surprising considering that minor fluctuations in velocity during swimming may have meaningful influences on performance due to elevation in energy cost caused by the high fluid resistance in this sport. As such, pacing is likely to have an even greater influence on overall performance in swimming compared to land-based endurance sports. The aim of this thesis was to determine if pacing is consistent in simulated and actual competitive events performed by highly-trained junior and elite swimmers, and determine the influence of pacing manipulation on overall performance during middle-distance swimming.

Methods: To analyse variability in pacing during simulated middle-distance swimming competition, highly-trained junior swimmers performed swimming events of varying distance (200 m, 400 m and 800 m) twice on separate occasions and under standardized conditions. Additionally, based on the world's top-50 swimmers of the year 2010 split times of 362 races (182 finals, 180 heats) of 158 different elite swimmers were analysed, retrospectively, to assess variability between and within real competitions. In order to examine the influence of pacing manipulation on middle-distance swimming performance the starting strategy of 400 m front-crawl races was manipulated. Within this study swimmers completed the initial 100 m slower (4.5% ± 2.2%) or faster (2.4% ± 1.6%) than a previous self-paced 400 m trial.

Results: The pacing pattern in middle-distance swimming seems to be consistent during simulated competitions in highly-trained junior swimmers, especially in the first three quarters of the race. Moderate manipulations of the starting speed during simulated 400 m front-crawl competitions seem to negatively affect overall performance. Nonetheless, seven out of fifteen swimmers recorded faster times during a manipulated trial (three when starting faster, four when starting slower).

Compared to highly-trained but junior swimmers elite athletes show an even smaller variation between competitions and within one event. Indeed, mixed modelling results revealed that within-subject standard deviation was higher compared to between-subject standard deviation leading to the hypothesis that variability in pacing seems to be related to the swimmer himself rather than to different competitors or competitions.

Discussion/Conclusion: High-level junior swimmers can perform middle-distance simulated competitions with high reproducibility. The theoretical hypothesis that pacing profiles are stable has been confirmed especially for the first three quarters of each event, however, the last quarter showed greater absolute variability. Variability in elite swimmers was small from one competition to the next as well as within one event, supporting the importance of prior experience. Whether the chosen pacing pattern, self-selected by athletes, is optimal for each individual swimmer remains unclear. Indeed, when manipulating pacing it was observed that some swimmers may not self-select an optimal pattern, since their performance improved. As such, the findings from this thesis indicate that individual swimmers may benefit from experimenting with small variations in pacing during training and competition in an attempt to find the individual pattern that works best under specific conditions. Future research should aim at identifying which athletes might benefit from pacing manipulation. Influencing factors may not be limited to physiological variables indicating ‘optimal’ pacing for an individual but could also include psychological factors such as personality aspects, affect, attentional focus, emotions and motivation.

Zusammenfassung

Einleitung: Für Ausdauersportler ist die Einteilung aller energetischen Ressourcen für eine optimale Gesamtleistung im Wettkampf von entscheidender Bedeutung. Dabei ist es wichtig, die Geschwindigkeit so einzuteilen, dass eine frühzeitige Ermüdung vermieden, aber dennoch die individuell bestmögliche Leistung erbracht wird. In der Sportwissenschaft wird dies als ‘pacing’ (zu dt. Renneinteilung) definiert. In den vergangenen Jahren hat das wissenschaftliche Interesse an ‘Pacingmustern’ und den zugrunde liegenden Mechanismen deutlich zugenommen. Es wird angenommen, dass die ‘Wahl’ einer bestimmten Pacingstrategie von Antizipation, Erfahrung, sensorischem Feedback sowie dem Wissen über die zurückzulegende Gesamtdistanz beeinflusst wird. Bislang wurden die meisten Pacingstudien im Rad- oder Laufsport durchgeführt. Zu pacing im leistungsorientierten Schwimmen gibt es bislang jedoch nur unzureichend Daten. Allerdings kann vermutet werden, dass (optimales) pacing gerade im Schwimmsport bedeutend sein könnte, da aufgrund des höheren Widerstandes im Wasser bereits minimale Veränderungen der Geschwindigkeit zu einer relevanten Erhöhung des Energieverbrauchs führen und dadurch die Gesamtleistung beeinflusst werden kann. Daher war es das Ziel dieser Dissertationsarbeit zu untersuchen, ob Pacingmuster von leistungsorientierten Juniorenschwimmern sowie von Weltklasse Schwimmern in simulierten bzw. realen Wettkämpfen gut reproduzierbar sind. In einem weiteren Schritt sollte der Einfluss einer Manipulation der Anfangsstrategie auf die Gesamtleistung in simulierten 400 m Rennen erfasst werden.

Methodik: Um die Variabilität von pacing bei leistungsorientierten Juniorenschwimmern zu untersuchen, wurden über drei verschiedene Strecken (200 m, 400 m und 800 m) je zwei simulierte Wettkämpfe innerhalb einer Woche unter möglichst standardisierten Bedingungen durchgeführt. Weiterhin wurden insgesamt 362 Rennen (182 Endläufe, 180 Vorläufe) von 158 verschiedenen Weltklasse Schwimmern (basierenden auf der Weltrangliste von 2010) retrospektiv analysiert, um die Variabilität zwischen bzw. innerhalb (Vor- zu Endlauf) von realen Wettkämpfen zu bestimmen. In einer abschließenden Studie wurde dann die Anfangsgeschwindigkeit in einem 400 m Kraulrennen manipuliert. Dabei sollten leistungsorientierte Juniorenschwimmer die ersten 100 m einmal 4.5% (± 2.2%) langsamer und einmal 2.4% (± 1.6%) schneller angehen als in einem zuvor durchgeführten selbst eingeteilten Rennen.

Ergebnisse: Es kann festgestellte werden, dass die Renneinteilung von leistungsorientierten Juniorenschwimmern innerhalb simulierter Wettkämpfen vor allem im ersten Drittel des Rennens gut reproduzierbar ist. Eine moderate Manipulation der Anfangsgeschwindigkeit hat insgesamt einen negative Effekt auf die 400 m Gesamtleistung, allerdings muss festgehalten werden, dass sieben von fünfzehn Schwimmern eine bessere Leistung in einem manipulierten Rennen zeigten (drei bei einem schnelleren, vier bei einem langsameren Start). Im Vergleich zu leistungsorientierten Juniorenschwimmern wurde bei Weltklasse Schwimmern sowohl zwischen als auch innerhalb eines Wettkampfes eine geringere Variabilität im Pacingmusters festgestellt. Aufgrund der Ergebnisse des gemischten linearen Modells kann angenommen werden, dass die Gesamtvariabilität eher auf die Variation innerhalb eines Schwimmers als dem externen Einfluss verschiedener Gegner und/oder Wettkämpfen zurückzuführen ist (höhere intraindividuelle Standardabweichung im Vergleich zur interindividuellen).

Diskussion/Schlussfolgerung: Leistungsorientierte Juniorenschwimmer zeigen in simulierten Mittelstrecken Rennen eine gute Reproduzierbarkeit ihrer Pacingmuster. Dabei wird die theoretische Annahme, dass Ausdauerathleten innerhalb ihrer Karriere ein stabiles pacing entwickeln vor allem für das erste Drittel eines Rennens bestätigt. Allerdings zeigte das letzte Drittel eine höhere Variabilität. Bei Weltklasse Schwimmer konnte sowohl von einem Wettkampf zum nächsten als auch innerhalb eines Wettkampfes eine geringere Variation im pacing festgestellt werden. Dadurch lässt sich annehmen, dass die Erfahrung aus früheren Rennen bedeutend für das Pacingmusters zu sein scheint. Allerdings ist bislang noch unklar, ob solch ein gefestigtes Muster bei jedem Athleten zur individuell besten Leistung führt. In diesem Zusammenhang konnte innerhalb der vorliegenden Dissertation bei sieben von fünfzehn trainings- und wettkampferfahrenen Schwimmern eine Verbesserung der 400 m Leistung gezeigt werden, wenn die Anfangsstrategie manipuliert wurde. Daher kann angenommen werden, dass einzelne Schwimmer davon profitieren könnten ihr gefestigtes Pacingmusters in Training und Wettkampf zu variieren, um die individuell beste Renneinteilung zu finden. Zukünftige Studien sollten versuchen mögliche Muster bei Athleten zu identifizieren, um besser beurteilen zu können in welchen Fällen eine selbstgewählte Renneinteilung nicht optimal sein könnte. Dabei sollten sowohl physiologische als auch psychologische (z.B. Persönlichkeit, Aufmerksamkeit, Emotionen und/oder Motivation) Einflussfaktoren berücksichtigt werden.

“I swam the race like I trained to swim it. It is not mathematical. I just let my body do it."

- Ian Thorpe

1 Introduction

Any athletic event inevitably has a beginning and an endpoint. In order to reach this endpoint in the fastest possible time, athletes need to appropriately distribute their energy expenditure, in a way that all available energetic resources are used but not so early so as to experience premature fatigue prior to the finish line (St Gibson et al. 2006). In sport science literature this has been termed as '*pacing*', '*pacing strategy*', '*pacing profile*' and/or '*pacing pattern*'. Ever since the tortoise beat the hare in the epic fable, the idea that pacing might be vital to performance has been present in people's mind. This concept is reinforced whenever an athlete leading a race slows down, or when a trailing athlete marginally fails to catch the leader because they commenced their sprint to the finish too late (Foster et al. 1994).

Since the differences in 'classical' physiological characteristics (e.g. maximum oxygene consumption (VO_{2max}), lactate thresholds) of top-level athletes are declining optimal pacing is becoming increasingly important to athletic success (Abbiss & Laursen 2008; St Gibson et al. 2006). Pacing can be considered as 'optimal' when the athlete has used all available energetic resources efficiently when crossing the finish (Abbiss & Laursen 2008; Foster et al. 1994). This can be crucial since speed needs to be balanced in a way that allows completion of the exercise task to the best of each athlete´s capacity without a premature decrease in intensity (Edwards & Polman 2012; Foster et al. 1994). Athletes and coaches have long recognised the importance of pacing and employed experience-based strategies to teach and practice optimal pacing. However, exercise scientists have only recently begun to pay considerable attention to the concept and its influence on athletic performance (Edwards & Polman 2012). Indeed, in an attempt to understand how energy is distributed during exercise, research in pacing has dramatically increased over recent years (Abbiss & Laursen 2008), with several different models proposing to explain the pacing 'phenomenon'. Such models include, the 'Central Governor Model' (Noakes et al. 2001), teleoanticipatory theory (St Gibson et al. 2006), pacing awareness model (Edwards & Polman 2013), psychobiological model (Marcora 2010; Pageaux 2014) or perception based model (Tucker 2009). Many of them share the belief that pacing appears to be regulated by a complex relationship between the brain and other physiological systems (Abbiss & Laursen 2008; St Clair Gibson & Noakes 2004). More precisely afferent sensory feedback from various physiological systems seems to be received and regulated within the brain (Marcora 2010; Noakes et al. 2001; Noakes et al. 2005; St Clair Gibson & Noakes 2004). Several other factors such as knowledge of the task duration or distance remaining, memory of prior experiences, motivation and mood are also believed to be important in the regulation of intensity (Abbiss & Laursen 2008; de Morree & Marcora 2013; Tucker 2009). Pacing seems to be influenced by many intrinsic (e.g. physiological, biomechanical and cognitive) and extrinsic (e.g. environment) factors (Abbiss & Laursen 2008; Foster et al. 1994) operating as a neural buffering process whereby exercise intensity is regulated to prevent premature physical exhaustion (Edwards & Polman 2012; Noakes et al. 2005; Tucker & Noakes 2009). This suggests that pacing is established in anticipation of and not after physiological system failure (Edwards & Polman 2012). It should be apparent that this protective buffering role of pacing can not purely be seen from a physiological perspective. As ones pacing strategy is an informed decision based on a number of past and present factors, it must also be considered a psychological issue (Edwards & Polman 2012; Renfree et al. 2014a). A central aspect within many of the models to explain pacing is the participants' perception of exertion, perception of effort and the task demands (de Koning et al. 2011; Noakes et al. 2001; St Gibson et al. 2006; Tucker & Noakes 2009). Based on this it seems that the interaction of physiological and psychological factors are crucial for the successful distribution of exercise intensity (Edwards & Polman 2012).

While it is generally accepted that the communication between the brain and several physiological systems is likely to be important in the regulation of exercise intensity (St Clair Gibson & Noakes 2004), little is known about the physiological, cognitive and/or environmental factors that affect or control the distribution of energy during exercise (Abbiss & Laursen 2008) and thus research helping to understand which pattern is optimal for different sports, distances and/or individuals is still lacking (Abbiss & Laursen 2008; St Clair Gibson & Noakes 2004). Moreover, while there has been increasing focus with regards to pacing in a variety of endurance sports (e.g. cycling (Abbiss et al. 2013; Cangley et al. 2011), running (Bath et al. 2012; Faulkner et al. 2011) or speed skating (Muehlbauer et al. 2010)) few researchers have yet attempted to understand pace selection in swimming. This is surprising since optimal pacing may be especially relevant to swimming since water resistance increases disproportionally with increasing velocity (Batchelor 1967; Maglischo 1993) leading to an exponential rise in energy expenditure with increasing swimming speed (Foster et al. 1994; Mauger et al. 2012). Since pacing is inextricably linked to the individual's fatigue development (St Gibson et al. 2006), swimmers who fail to pace appropriately will eventually underperform.

To summarize, different pacing profiles have been described for different durations and/or types of sports, yet it still remains a controversial issue what constitutes successful pacing in swimming.

2 Background

2.1 Defining Pacing

Exercise tasks can be defined as either ‘open’ or ‘closed-loop’ events. ‘Open-loop’ tasks (also known as open end tests) are those whereby athletes or participants are required to exercise at a constant power or velocity for as long as possible. Conversely, ‘closed-loop’ events have a defined start and endpoint (e.g. time trials). Most competitive endurance events are considered to be of a ‘closed-loop design’, in which the individual has sufficient time to consider the implications of sensory neural feedback and consequently modify action to finish a known distance in the shortest possible time (Abbiss & Laursen 2008; Edwards & Polman 2012; Padilla et al. 2000; St Gibson et al. 2006). In this regard pacing strategy can be defined as

‘*The goal directed distribution and management of effort across the duration of an exercise bout’* (Edwards & Polman 2012)

Within ‘closed-loop’ events, athletes may compete in head-to-head competitions (e.g. in mass participation events), or individually against the clock (e.g. time trial) (Abbiss & Laursen 2008). In individual time trials the overall results are largely determined by the absolute time required to complete a given distance whereby the actions of a competitor has a lower influence on an athlete’s performance (Coyle 1999). As a result, such formats can be conducted in the laboratory, making it possible to somewhat replicate true competition and allowing modelling of performance (Abbiss & Laursen 2008; Billat et al. 1999; de Koning et al. 1999; Swain 1997). In head-to-head competitions, where success is determined by performing marginally better than other competitors, the actions of opponents or team members influence race dynamics and thus pacing pattern making it more complicated to simulate all influencing factors in a research setting. In head-to-head events athletes seem to emphasis on retaining a reserve of energy required for a final spurt to possibly outsprint an opponent in the last meters (Foster et al. 1993a). In contrast, the pacing pattern in prolonged (> 2 min) time trials tends to be more even as the aim is simply to finish the race in the shortest possible time (Edwards & Polman 2012). In general, athletes seem to learn their pacing in training as a consequence of practice and ‘trial-and-error’, most likely influenced by observations of other successful athletes (Foster et al. 1994).

Several models suggest, that during exercise the brain uses afferent information sent from the periphery to modify intensity (Marcora 2010; Noakes 2000; Pageaux 2014; St Clair Gibson & Noakes 2004). This is further influenced by self-awareness (Edwards & Polman 2013), previous experience of similar distance or duration (Mauger et al. 2009), environmental, and situational considerations (Renfree et al. 2014a). Greater self-awareness of the athletes' capabilities and the circumstances of the task can optimize this strategy leading to a reduced likelihood of misjudgement in pace (Lambert et al. 2005; Micklewright et al. 2010). Indeed, it has been suggested that in many exercise situations there is only a short time to deliberately plan a strategy or even adjust a predetermined race plan (Edwards & Polman 2012). It is worth noting that a strategy is defined as a cognitive process of planning action/s designed to achieve a particular goal (Foster et al. 1994). Since it is still unknown if a observed pacing pattern is based on a conscious decision-making process, a subconscious regulation of intensity based on afferent feedback or a combination of both, it might be more appropriate to refer to pacing as a 'pattern' or a 'profile' instead of using the term 'strategy'.

2.2 *Models to Explain Mechanisms of Pacing*

The regulation of pace is thought to be primarily dictated by the ability of an athlete to resist fatigue (Abbiss & Laursen 2008). However, the responsible mechanisms are currently unclear. In an attempt to understand these mechanisms and explain intensity distribution across a variety of exercise tasks, several researchers have proposed a number of models. These models are briefly outlined below.

2.2.1 The *Teleoanticipatory Hypothesis* and the *Central Governor Model*

In general, homeostasis acts to maintain physiological systems within a normal range (Thompson 2014). Self-paced exercise performance is thought to be regulated by the brain to prevent changes in physiological systems that might be detrimental to performance or health (Tucker & Noakes 2009). Hill and colleagues first proposed this idea in 1924. The authors referred to a 'controller somewhere in the body responsible for the regulation of oxygen delivery to the heart' (Hill et al. 1924). If afferent chemoreceptors detect a shortage of oxygen, the 'controller would send a command via the nervous system to reduce the recruitment of the heart's muscle fibres and subsequently slow down the heart rate and exercise intensity (Hill et al. 1924). In the 90's a similar concept was proposed by Ulmer (1996) suggesting that the self-selection of exercise intensity may be controlled in a teleoanticipatory manner, whereby athletes anticipate the work required to complete a given exercise task. Ulmer (1996) assumed that the principles of motor command are based on a feedback system, whereby efferent signals are send back to the periphery through afferent somatosensory channels to optimize movement with respect to metabolic cost (Ulmer 1996). Within this system the knowledge of the endpoint is used as an anchor for creating the particular algorithm for a certain exercise bout and moderating intensity during this bout (Ulmer 1996). All these factors then enable the athlete to anticipate the end point of the exercise task and to construct an internal pacing template for the event (St Clair Gibson & Noakes 2004). These anticipatory process has been called *Teleoanticipation* and includes the hypothesis of an extracellular system (similar to the 'controller' proposed by Hill et al.) to control metabolic rate in the muscles during exercise, including the somatic nervous system and behavioural psychophysiological mechanisms (Figure 1) (Ulmer 1996).

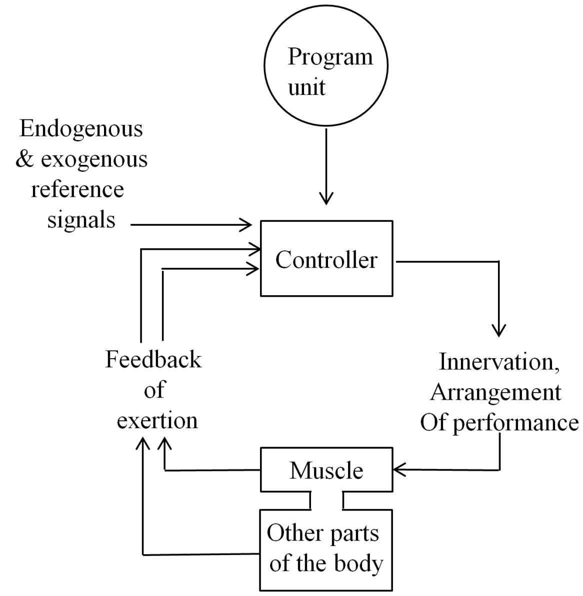

Figure 1 Hypothetical model of a control system for optimal adjustment of performance during heavy exercise, including teleoanticipation by a programmer (replicated from Ulmer 1986).

St Clair Gibson (2006), Noakes (2001; 2005; 2011) and Tucker (2009; 2009) have expanded and combined these concepts and theories and proposed a *Central Governor Model*. This governor has been suggested to be based somewhere in the brain or the heart and continuously regulates intensity throughout an event to provide premature fatigue (Noakes 2011). This regulation is based on a complex algorithm involving peripheral sensory feedback and the anticipated workload remaining (St Clair Gibson & Noakes 2004; St Gibson et al. 2006). In this *Central Governor Model* fatigue is described as part of a regulated anticipatory response believed to be coordinated in the subconscious brain to preserve homeostasis in each physiological system (Noakes & Gibson 2004). In this regard, St Clair Gibson et al. (2006) postulates that all alterations in exercise intensity require the ‘governor’ to monitor whether these changes are relevant for finishing the race in the shortest time possible. According to Noakes (2011) a wide range of factors such as oxygen delivery, metabolic fuel reserves, body temperature increase, metabolic accumulation, current environmental conditions, health status as well as psychological factors are included to regulate intensity and thus the athlete’s overall pacing (Noakes 2011) (Figure 2).

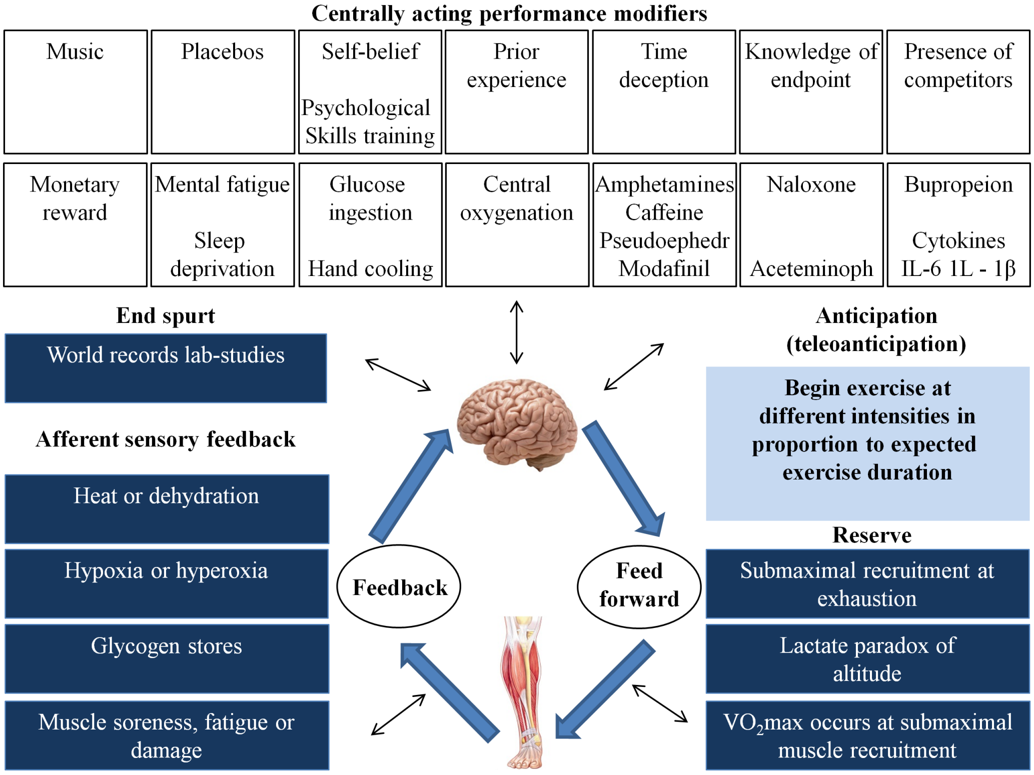

Figure 2 Factors affecting how the pace is set and regulated during an event (replicated from Noakes 2011).

Based on all this information an algorithm is generating a pacing template appropriate to prevent premature fatigue and at the same time ensure optimal performance (St Gibson et al.

2006). During the sporting event afferent input from metaboreceptors, nociceptors, thermoreceptors, cardiovascular pressure receptors and mechanoreceptors continuously monitor if crucial changes in any physiological system might be associated with the chosen intensity and if the algorithm needs to be adjusted (Arbogast et al. 2000; Haouzi et al. 1999; Lambert et al. 2005; Rauch et al. 2005). Conversely, if the pace is too slow, the efferent neural commands are increased to create higher power output or speed (St Gibson et al. 2006). In support of such a central regulation of exercise intensity, numerous studies have been shown that variations in power or speed are accompanied by changes in integrated surface electromyography (iEMG) (St Clair Gibson et al. 2001b; Tucker et al. 2004). Indeed, it has been observed that reductions in iEMG are in line with a declined power output during repeated 1 and 4 km high-intensity bouts during a 100 km cycling time trial (St Clair Gibson et al. 2001b). Therefore, the *Central Governor Model* proposes that muscle power output is continuously modified throughout the exercise bout using an integrative control algorithm presumably a centre in the subconscious brain (Figure 3) (St Clair Gibson et al. 2005; 2006).

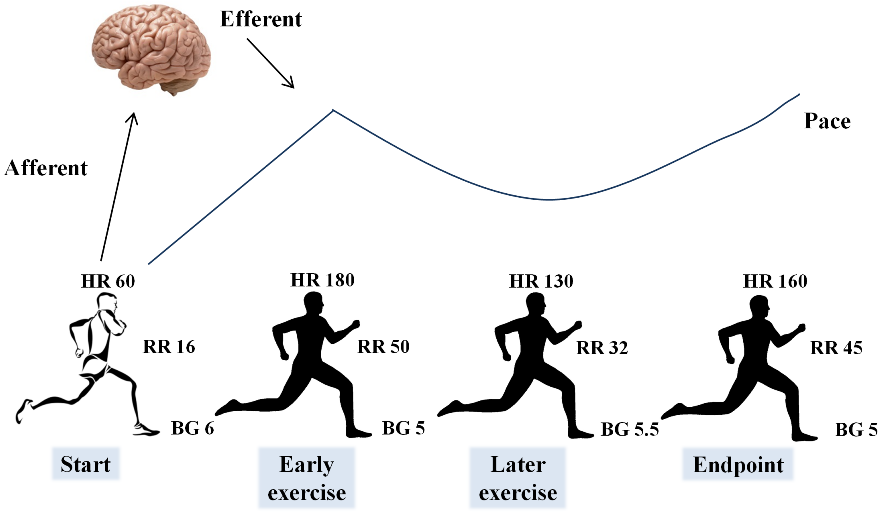

Figure 3 The ‘teleoanticipatory’ regulation of intensity during exercise. Afferent information from receptors recording changes in peripheral physiological system variables such as heart rate (HR), respiratory rate (RR) and blood glucose concentrations (BG) is send to the ‘teleoanticipatory governor’ during the exercise task (replicated from St Gibson et al. 2006).

The anticipatory *Central Governor Model* has been widely debated and criticised on several levels (Hopkins 2009; Levine 2008; Shephard 2009). For example, contrary to St Clair Gibson et al. (2001b) and Tucker et al. (2004) other research groups showed that iEMG may remain unchanged or might even increase despite a decline in power output (Hettinga et al.

2006). Many researchers further criticize that Noakes and colleagues assume that the *Central Governor* is a '*subconsciously reacting regulator somewhere in the central nervous system*' operating like 'a little man' within our body (Edwards & Polman 2013). Based on this, further models have been proposed suggesting that pacing is not necessarily dictated by one centrally controlled programmer but by complex integration of various physiological processes.

2.2.2 The *Psychobiological Model* of Pacing

Marcora (2010) and Pageuax (2014) recently proposed that self-paced endurance performance can be predicted by a *Psychobiological Model* which is based on the Motivational Intensity Theory published by Brehm & Self (1989). This model postulates that the conscious regulation of pace is determined primarily by five different cognitive/motivational factors (Pageaux 2014):

1. Perception of effort
2. Potential motivation
3. Knowledge of the distance/time to cover
4. Knowledge of the distance/time remaining
5. Previous experience/memory of perception of effort during exercise of varying intensity and duration

According to Pageaux (2014) the athlete's perception of effort is the key determinant of this model and can be defined as '*the conscious sensation of how hard, heavy and strenuous an exercise task is*' (Marcora 2010). In this model the conscious regulation of pace is primarily determined by the effort perceived by the athlete (Pageaux 2014). When perceived effort is increased by muscle (de Morree & Marcora 2013) or mental (Pageaux et al. 2014) fatigue, or reduced by pharmacological manipulation (Burns et al. 2012), the athlete will consciously change the pace to compensate for the negative/positive effect of the manipulation. Marcora (2009) and De Morree (2012) further propose that the perception of effort results from the central processing of the corollary discharge model associated with central motor command (Figure 4).

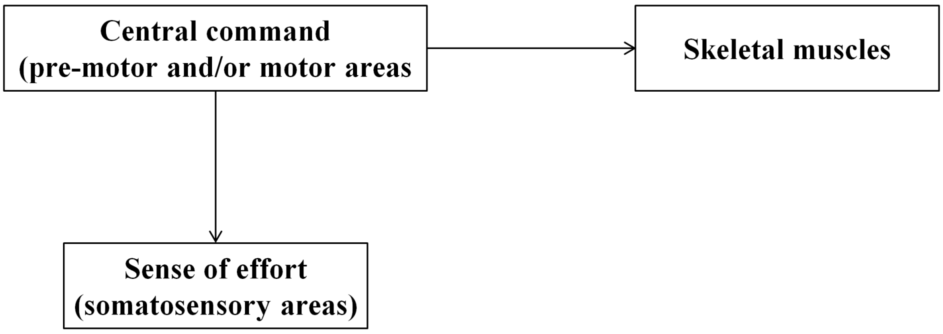

Figure 4 Simplified corollary discharge model of perceived effort (replicated from Marcora 2009)

This well accepted theory postulates that an efference copy of the central motor command is sent directly from motor to sensory areas of the brain in order to assist in the generation of perceptions associated with motor output (Bubic et al. 2010; Christensen et al. 2007; Enoka & Stuart 1992; Poulet & Hedwig 2007). As such, the close relationship between rating of perceived exertion (RPE) and muscle activity (i.e. EMG) during exercise is thought to be largely influenced by a central feed forward neurophysiological mechanism whereby as motor unit recruitment and firing frequency increase, the number of efferent copies received by sensory regions within the brain also increases (de Morree et al. 2012; Lagally et al. 2002).

It should be noted that Marcora (2009) and De Moree (2012) refer to Borg's RPE scale (Borg 1982) as a measurement of perceived *effort*, which was, however, originally introduced as a rating of perceived *exertion*. It has been proposed that the *exertion*, which may be associated with physical and physiological stress induced as a result of exercise, is distinctly different from an athlete's perceptions of *effort* (Smirmaul 2012; Swart et al. 2012a). Indeed, exertion has been defined as the '*degree of heaviness and strain experienced in physical work*' whereas, effort may be defined as *'the amount of mental or physical energy being given into a task'* (Borg 1998). The issue in the use of the terms *effort* and *exertion* within the context of the use of RPE is likely to be relatively minor in regards to monitoring psychophysiological stress or a set exercise intensity. However, directions given to participants when introducing this scale could influence their response and thus might have considerable implications in understanding the role of RPE within the regulation of self-paced exercise and particularly with regards to the *Psychobiological Model*. For example, De Morree & Marcora (2013) observed significantly higher RPE values with a corresponding lower power output at the beginning of a 15 min cycling time trial after a pre-exercise eccentric fatiguing protocol. The authors state, that maintaining the same pace with fatigued locomotor muscles resulted in higher RPE values possibly leading to premature fatigue (de Morree & Marcora 2013). Hence, participants decided to reduce their pace so RPE does not reach its maximum before the end of the trial. In contrast, another study showed significantly lower power output during a pre-fatigued 40 km cycling time trial compared to a non-fatigued one, without differences in corresponding RPE values (Skorski et al. 2014). Together, these findings highlight that even though RPE is seen as the important variable in the *Psychobiological Model* to explain self-paced exercise there might be discrepancies in interpreting the scale leaving the role of perceived exertion and/or effort on pacing open for future discussions.

Proposing that the regulation of intensity during exercise is a conscious process is probably the greatest differential between the *Psychobiological Model* and the *Central Governor Model* or the *Teleonaticipation Theory* (Chapter 2.2.1). Indeed, the *Central Governor* is assumed to act subconsciously on the bases of afferent feedback from various physiological systems (Tucker 2009), while the *Psychobiological Model* postulates that the athlete is consciously deciding to increase or decrease intensity throughout the race. Another recently proposed model, the *Pacing Awareness Model,* similarly assumes a rather conscious regulation of exercise intensity.

2.2.3 The *Pacing Awareness* and the *Informed Decision-Making Model*

Edwards & Polman (2013) propose an exercise regulation model which in some way combines the *Central Governor* and the *Psychobiological Model*. Similar to Noakes' *Central Governor* the *Pacing Awareness Model* suspects that exercise is centrally regulated and that this regulation includes prior experience, knowledge of distance and sensory feedback (Edwards & Polman 2013). However, the authors specifically state that the *conscious* brain functions as this regulator, continuously monitoring physiological systems via feed forward and feedback loops. Edwards & Polman (2013) further propose that pacing should not be investigated purely from a physiological perspective but rather considered an *informed decision process*, which is based on knowledge of past and present factors and intrinsic knowledge of the physical capabilities (Edwards & Polman 2013; Mauger et al. 2009; Micklewright et al. 2010; St Clair Gibson & Noakes 2004). Indeed, Renfree et al. (2014a) recently stated that decision-making should be seen as an integral part of athletic competition, however, little is understood about how decision-making processes influence pacing. In their recent review, the authors define decision-making as the process of making a choice from a set of options where the consequences of that choice are crucial (Bar-Eli 2011; Renfree et al. 2014a). In the context of regulating self-paced exercise it would seem that athletes are required to continually make decisions (Renfree et al. 2014a), such as the decision to increase power output to achieve the best possible outcome but still manage power output due to the fear of system failure (Edwards & Polman 2013). In this regard, athletes voluntary reduce intensity well in advance of any physical necessity to do it, when they are confronted with adverse, unfamiliar conditions (Dugas et al. 2009; Marino 2004). Thus, it seems that pacing is established in anticipation of and not after physiological system failure (Edwards & Polman 2013; Marino 2004), and is functioning as a buffering process to distribute effort and prevent premature exhaustion (Edwards & Polman 2013; St Clair Gibson & Noakes 2004). Renfree et al. (2014a) further proposed that the decision to reduce, increase or maintain efferent neural drive depends on the perceived benefits to be obtained from each alternative, which is based on the rational decision-making model by Simon (1955). When perceived 'payoff' is potentially large (e.g. victory, achieving a personal best or enjoyment of the experience) an individual would be more likely to incur a greater degree of homeostasis disruption or even harm (Figure 5) (Renfree et al. 2014a).

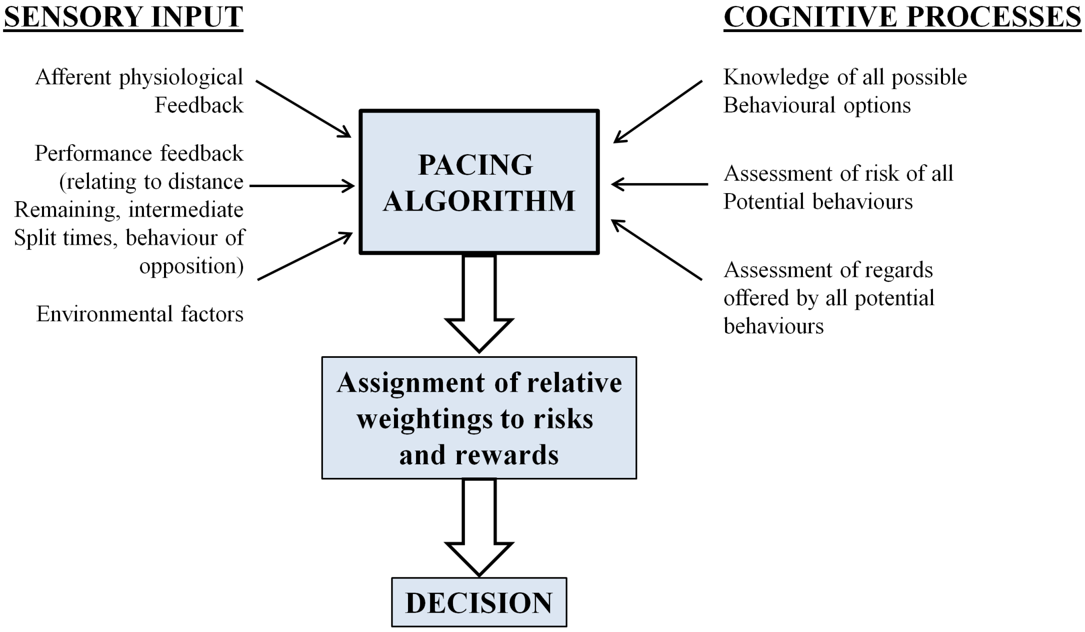

Figure 5 Rational model of the process leading to the making of a decision regarding exercise intensity (replicated from Renfree et al. 2014a).

In contrast to Noakes' theory supposing *subconscious* exercise regulation and also contrary to the *Psychobiological Model* proposing a complete *conscious* regulation, the *Pacing Awareness* and the *Informed Decision-Making Model* assume that intensity regulation occurs via different states of awareness influencing the athlete's decision. The complex neural communications within the brain predominantly act without the need for conscious awareness (Edwards & Polman 2013; Magill 2011). When afferent sensations of metabolic disturbances are sufficiently compelling, the athlete's conscious attention is gained to possibly change behaviour (Edwards & Polman 2013). It is known that sensory information is received in the thalamus and communicated to the primary sensory cortex within the parietal lobe (Whittow 1999). A great deal of information acting on the motor cortex to stimulate muscle recruitment (e.g. memories from the hippocampus or information from the brainstem on body temperature, hunger or thirst) is transferred without conscious awareness (Magill 2011). Based on neuroscientific and psycho-analytic studies, it seems that humans are often not conscious or not aware about many 'routine' events in their body. This is because a lot of those body experiences usually do not reach the cerebral cortex for higher-order neural processing unless they challenge homeostasis (Crick & Koch 1995; Edwards & Polman 2013; Gazzaniga 1996). Humans are executing several physical tasks without much of awareness to them, such as changing the gear at the appropriate time in the car, however all these tasks require motor unit recruitment, which is regulated by the same neural processes as for example movement during exercise, but without the awareness of the conscious mind (Magill 2011). If a situation (i.e. exercise or movement) becomes more aware it is usually the consequence of increasing negative cues such as sensations of thirst, nausea or overheating (Edwards & Noakes 2009; Edwards & Polman 2013). Thus, during high-intensity exercise, the severity of such sensory cues eventually triggers awareness (Edwards & Polman 2013; Swart et al. 2012a). At low levels of physical effort, regulatory control can be accomplished with minimal awareness, but still be maintained by the brain. As mentioned previously, regulatory afferent information is constantly passed to the thalamus from the peripheral nervous system (Portas et al. 1998), yet the majority of the time it does not receive our complete attention or awareness. Hence, Edwards & Polman (2013) propose that pacing is an extension of brain regulatory control operating at different levels of awareness (from minimum like sleep to a maximum of full awareness) within a conscious state. If the stimulus from the periphery gains intensity it seems to reach a level of awareness to increase attention and requires controlled behaviour (Edwards & Polman 2013; Swart et al. 2012a). Acceptable limits of automaticity seem to be based on prior experience and/or expectations of the task demand. Thus, afferent feedback on peripheral status is analysed to gauge the current status, and then categorized through comparison with physiological set point values in order to ascertain if the current intensity is 'safe' (Renfree et al. 2014a). When sensory feedback increases the brain seems to arouse a controlled response in need of controlled behaviour. Figure 6 displays a comparison of the brain regulation within the different regulation models: the *Central Governor*, the *Psychobiological* and the *Pacing Awareness Model*. The latter suggesting that the brain is continually in a conscious state, yet regulatory control of exercise might be considered as a regulation via relative states of awareness rather than a conscious or subconscious states (Edwards & Polman 2013).

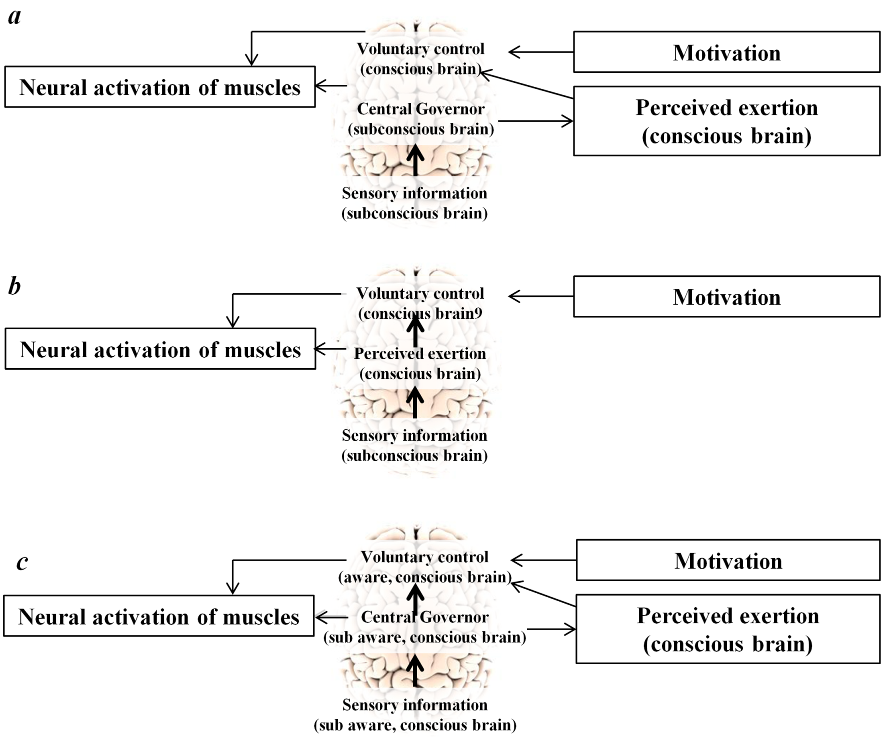

Figure 6 A comparison of brain regulation models of human movement: (***a***) *Central Governor Model*; (***b***) *Psychological Model*; (***c***) *Conscious Awareness Regulation Model* (replicated from Edwards & Polman 2013).

It is noteworthy that the RPE-scale might be considered to represent the integration of all signals, perceptions and experiences combined into a single 'gestalt' assessment (Borg 1982). As previously mentioned several authors suggest that RPE can be considered as a primary regulator of muscular work rate (Borg 1982; Renfree et al. 2014a), hypothesising that the current RPE is continually compared with a 'template RPE' to reduce neural drive if the present RPE exceeds the template or increase if it is below (Renfree et al. 2014a). The RPE seems to be generated via interpretation of afferent information regarding physiological status, whereas the template is set in advance of the exercise bout to ensure that maximal tolerable levels of RPE are not achieved prior to reaching the endpoint of the bout (Renfree et al. 2014a). As highlighted above (Chapter 2.2.2) the instructions provided to participants when introducing RPE scale/s is likely to influence the measured outcomes especially since athlete's are able to differentiate between both perceptions of effort and exertion (Swart et al. 2012b). To date, few studies have examined numerous perceptions during exercise and thus the potential difference, importance and relationship between these variable is not well understood. It appears that perceptions of both exertion and effort are regulated within various regions of the brain based on the integration of information relating to motor drive, afferent feedback and numerous other factors including prior experience, awareness and motivation. To address this issue, studies designed to independently assess both effort and exertion are needed to provide a better insight into self-paced exercise.

To summarize, there are several different models that attempt to explain how the individual regulates intensity or effort during exercise. Between these models the relative contribution and influence of peripheral and central fatigue is still controversial. Whilst the majority acknowledges that the brain has an influence within this regulation there is considerable disagreement if athletes are consciously deciding to change the pace (Pageaux 2014), if intensity is subconsciously regulated (Noakes et al. 2005) or if the brain works on different levels of awareness (Edwards & Polman 2013). Most authors agree that the subjective feeling of effort or exertion seems to have an important role on an athlete's pacing pattern. The current models include many theoretical assumptions, which is most likely due to the technical difficulties related with brain measurements during exercise. With experimental evidence missing it seems to be an ongoing discussion what constitutes pacing during athletic performance.

2.3 Describing Pacing Pattern

As described in the previous chapters the regulation of pace is closely linked to the ability to resist fatigue (Abbiss & Laursen 2008). By modelling power/velocity relationships and observing athletic performance during varying competition scenarios coaches and researchers have been able to gain some insight into what might constitute optimal pacing (Abbiss &

Laursen 2008; Arsac & Locatelli 2002; van Ingen Schenau et al. 1992; Wilberg & Pratt 1988). In particular, short-duration sprint events (e.g. < 30 to 60 seconds) benefit from an '*all-out*' pattern (Abbiss & Laursen 2008; van Ingen Schenau et al. 1992; Wilberg & Pratt 1988), whereas for prolonged endurance performance a more *evenly* distribution of energy resources is beneficial (Abbiss & Laursen 2008; de Koning et al. 1999). In fact, a variety of pacing profiles have been observed during different exercise tasks and under differing conditions (Foster et al. 1994; St Gibson et al. 2006). These include *negative*, *all-out*, *positive*, *even*, *parabolic-shaped*, and *variable* pacing profiles. These profiles have been summarized by Abbiss & Laursen (2008). The following chapter is based on this review and provides a brief overview of the different pacing profiles observed in athletic events.

2.3.1 Negative Pacing

A pacing pattern can be defined as *negative* when speed or power increase over the duration of an event (Abbiss & Laursen 2008). This profile has mostly been observed in middle-distance events (< 2 minutes), when athletes become aware of the remaining distance or duration and increase power output (Albertus et al. 2005; Foster et al. 2004; Tucker et al. 2004) or velocity towards the finish (Foster et al. 2004) (Figure 7). Some authors assume that a slower start might reduce the rate of carbohydrate depletion (St Gibson et al. 2006), lower oxygen consumption (Sandals et al. 2006), and/or limit accumulation of fatigue-related metabolites (such as inorganic phosphate) at the beginning of the race, thus improving performance (Abbiss & Laursen 2005; Mattern et al. 2001). Supporting this, Mattern et al. (2001) observed significantly lower blood lactate concentrations during the initial phase of a slow-start 20 km cycling time trial, combined with a better overall performance compared to a self-paced trial. It is believed that the increase in intensity towards the end may be the result of an increase in motor unit recruitment (Tucker et al. 2004) and a greater use of anaerobic pathways (Foster et al. 2004).

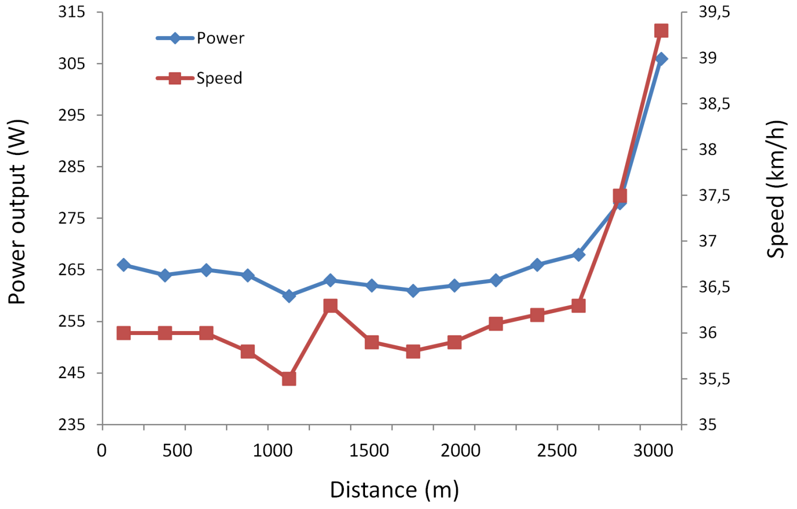

Figure 7 Speed and power output profiles during 3000 m track cycling events (replicated from Abbiss & Laursen 2008).

2.3.2 All-Out Pacing

In short duration or short distance events (< 1 minute), the majority of the energy expenditure is required to alter the body's kinetic energy from rest to movement. In fact, approximately 60% of the overall performance time during a 100 m sprint is spent in this acceleration phase (Tibshirani 1997). Since, increasing momentum leads to increasing kinetic energy, a lower amount of energy is needed to maintain a constant pace throughout the remaining event. In short duration events the initial acceleration phase is proportionately longer than other stages of the event, and as such, submaximal movement speed at the start of an event are likely to result in slower overall performance times (Abbiss & Laursen 2008; van Ingen Schenau et al. 1992). Thus, it is believed that the majority of energy during short events is best distributed at the start leading to an *all-out* pacing pattern (Abbiss & Laursen 2008) (Figure 8). This might be a bit different in swimming since the dive start allows athletes to rapidly accelerate to race speed without spending a lot of their energy. However, in support of the *all-out* strategy mathematical models and physiological constants calculated from previous world record times determined that during running events under 291 m an *all-out* pacing (theoretically) results in optimal performance (Keller 1974). This model seems plausible as anaerobic energy resources are significantly reduced after 30 to 60 sec of all-out sprinting (Yamamoto & Kanehisa 1995). De Koning et al. (1999) observed that cyclists performed considerably better when releasing a large amount of anaerobic energy early in the race. High initial power output, as in an *all-out* strategy, results in a considerably greater amount of energy lost to friction compared to a constant pace, yet kinetic energy at the end of the race is lower (de Koning et al. 1999). Considering that during a time trial, any velocity/energy that exists after passing the finish line is essentially wasted kinetic energy, it seems that the advantage of a higher acceleration and a lower amount of 'waste' at the end outweigh the disadvantage of higher friction losses associated with higher mean velocity (Abbiss & Laursen 2008; de Koning et al. 1999; van Ingen Schenau et al. 1992). The longer the event, the less important kinetic energy loss becomes relative to the cost of aerodynamic/hydrodynamic resistance (Abbiss & Laursen 2008; Arsac & Locatelli 2002; Atkinson & Brunskill 2000; Atkinson et al. 2003; Foster et al. 1993b; Foster et al. 2004; Swain 1997).

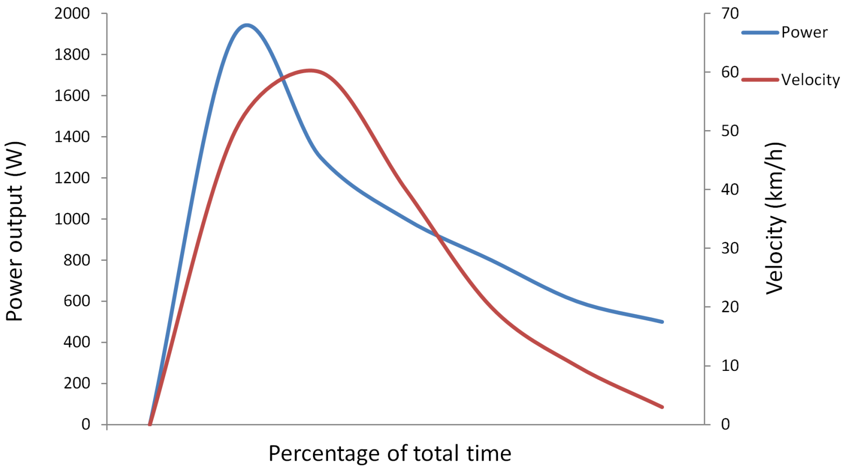

Figure 8 Example of power output and velocity profiles during a 1000 m track cycling event (replicated from Abbiss & Laursen 2008).

2.3.3 Positive Pacing

A *positive* pacing pattern is defined as a decrease in speed, power and/or increase in time throughout the duration of an event (Abbiss & Laursen 2008) (Figure 9). For example, this pattern has been observed in 100 m and 200 m breaststroke swimming (Thompson et al. 2000), 2000 m rowing (Garland 2005) and 800 m running (Sandals et al. 2006). However, increased oxygen consumption (VO_2) (Garland 2005; Sandals et al. 2006), greater accumulation of fatigue-related metabolites (Thompson et al. 2003; Thompson et al. 2004) and an increase in the RPE (Thompson et al. 2004) have been associated with such a *positive* pacing pattern. In this regard it has been speculated that the adaptation of a *positive* pacing is a result of a gradual reduction in exercise intensity associated with fatigue in response to these signals (Abbiss & Laursen 2008; Marino 2004; Noakes et al. 2005; Thompson et al. 2004). This supports the hypothesis, that pacing may be a neural buffering process to avoid premature exhaustion. Tucker et al. (2004; 2006b) showed that power output in well trained cyclists declined at a significantly greater rate in hot (35ºC) compared to cool (15 ºC) conditions (2.35 ± 0.7 vs. 1.61 ± 0.8 W/min), hypothesizing that exercise intensity is continuously manipulated to avoid the development of critically high core temperatures (> 39.5ºC) (Abbiss & Laursen 2008; Tucker et al. 2006b). Interestingly, Castle et al. (2012) recently observed that cyclists did not show any impairment in performance when they were deceived into thinking they were cycling in an ambient temperature of 26.0 instead of 31.6ºC. This is in contrast to the hypothesis by Tucker et al. (2004; 2006b) that power output is (subconsciously) down regulated in the heat. It is further surprising that athletes in these two earlier studies by Tucker et al. self-selected a high initial power output (> 370 W) in the heat rather than choosing a lower intensity from the start. This might be either related to the lack of thermal stress at the beginning of the trial (Abbiss & Laursen 2008) or the influence of the pacing template based on prior experience and stored in the long-term memory (Mauger et al. 2009; Micklewright et al. 2010). Abbiss & Laursen (2008) further discuss the possibility that the relatively fast start may be the result of unrealistic ambitious perceptions regarding the athletes' personal ability. They might begin the race at a pace designed to finish within the medallists or at the personal best, which often results in a progressive reduction in intensity due to fatigue (Foster et al. 2004). It has further been observed that the self-selected intensity during ultra-endurance events (> 4 hours) tends to progressively decrease throughout the race (Abbiss et al. 2006; Lambert et al. 2005; Laursen et al. 2005). Authors believe that this is the result of increased glycogen depletion (Rauch et al. 2005), resulting in altered substrate utilization (Neumayr et al. 2002), neuromuscular fatigue (Abbiss & Laursen 2005; Laursen & Rhodes 2001) and/or psychological factors associated with perception of fatigue (Abbiss & Laursen 2005; Laursen & Rhodes 2001; St Clair Gibson et al. 2003).

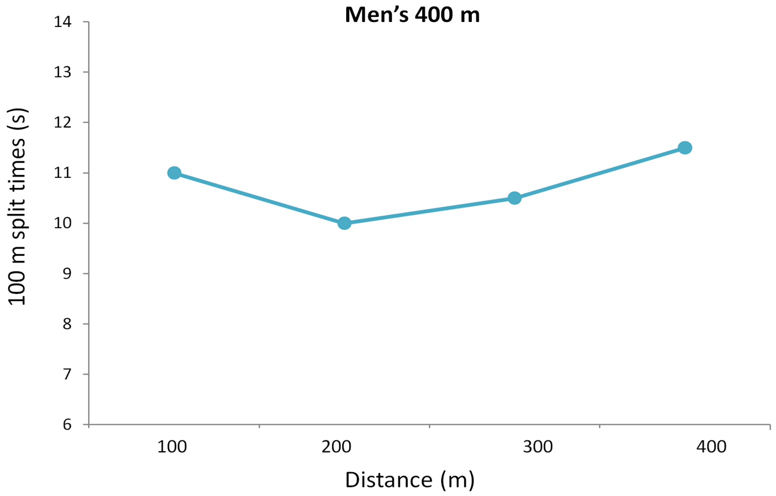

Figure 9 Example of a typical velocity profile in the 400 m running event (replicated from Thompson 2014).

2.3.4 Even Pacing

It has been suggested that under stable environmental conditions a constant or *even* pace (Figure 10) is 'optimal' for prolonged events (> 2 min) in running, rowing, swimming, skiing, speed skating or cycling (Abbiss & Laursen 2008; de Koning et al. 1999). The theoretical support for this assumption is primarily based on critical power models and mathematical laws of motion, which indicate that velocity is dictated by the maximal constant forces experienced (Billat et al. 1999; di Prampero et al. 1979; Fukuba & Whipp 1999; Morton 2006). For example, Fukuba & Whipp (1999) used mathematical modelling to observe that an athlete's performance will be compromised if velocity drops below the physiological limit (described as critical velocity) at any point during an endurance event, even if the athlete tries to make up for this lost time with a final increase in speed towards the end of the race. Increasing velocity inevitably results in greater 'fluid' (e.g. air or water) resistance, hence, an increasing percentage of the power generated needs to be used to overcome this resistance (Abbiss & Laursen 2008). This is even more important during water-based sports such as swimming or rowing compared with land-based sports. Water-based sports induce a higher energetic demand with increasing speed due to the higher resistance of the element water compared to air (Maglischo 1993; Zamparo et al. 2005). Thus, even minor fluctuations in velocity can result in a greater energy cost and thus might have a greater impact on overall performance (Smith et al. 2002; Thompson 2014; Zamparo et al. 2005).

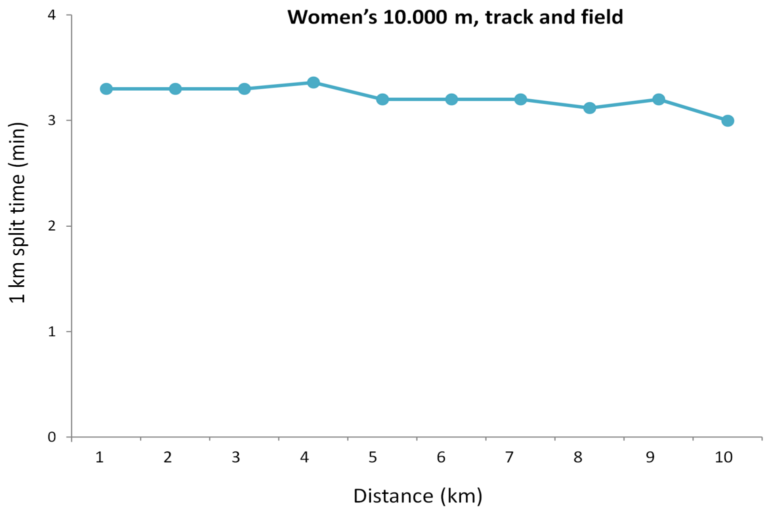

Figure 10 Example of a velocity profile in the 10.000 m track and field event (replicated from Thompson 2014).

2.3.5 Parapolic-Shaped Pacing

During endurance trials athletes seem to progressively reduce speed during the middle part of a trial but tend to increase intensity during the later portion of the event (Abbiss & Laursen 2008; Garland 2005; Tucker et al. 2004). This results in a *U*, *J* or *reverse J-shaped* pacing pattern (Figure 11).

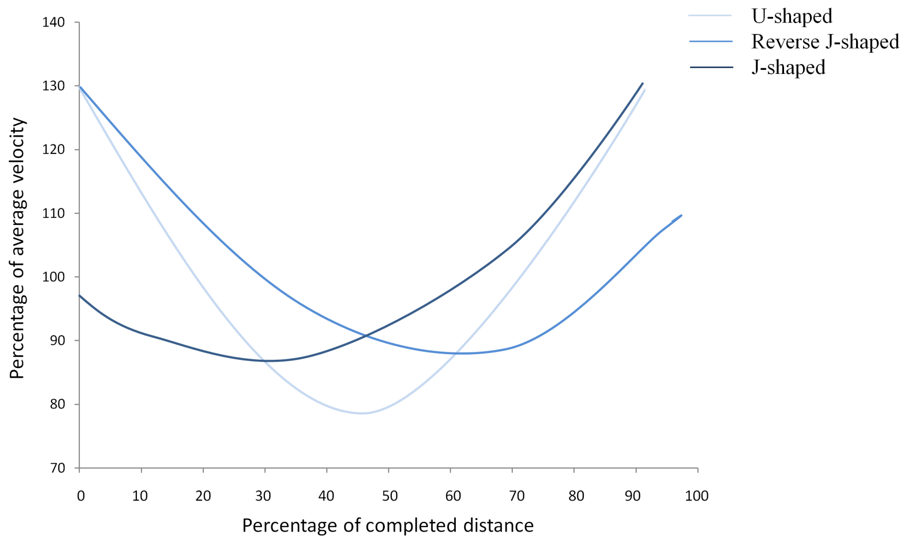

Figure 11 Example of U-shaped, reverse J-shaped and J-shaped pacing pattern during exercise (replicated from Abbiss & Laursen 2008).

Garland (2005) observed such a pattern in the 2000 m rowing events of the 2000 Olympic Games, 2000 and 2002 World Championships and the 2001 and 2002 British Indoor Rowing Championship. In each of these races, rowers completed the first 500 m in the fastest time, slowed down in the middle 1000 m but increased speed during the final 500 m, resulting in *reverse J-shaped* pacing (Garland 2005) (Figure 12).

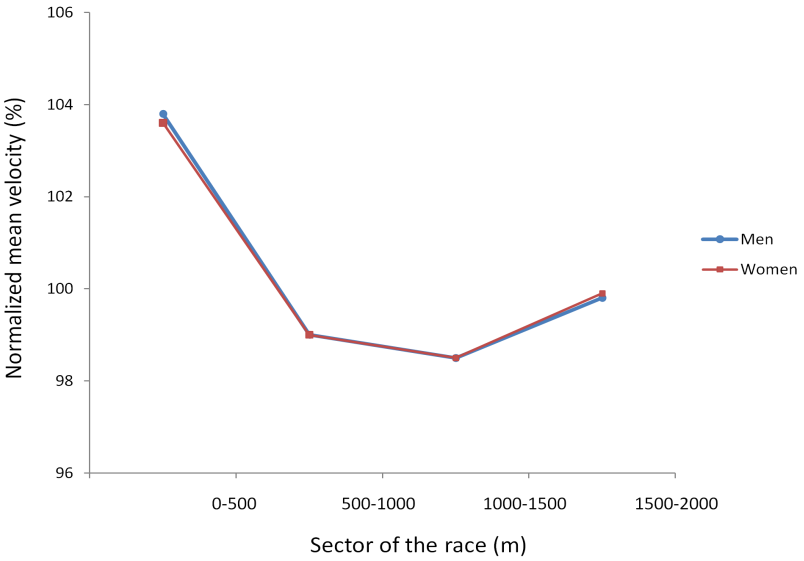

Figure 12 Example of a reverse J-shaped pacing pattern observed during the 2000 m rowing championship (replicated from Abbiss & Laursen 2008).

This type of *parabolic shaped* pattern has been commonly reported in a variety of exercise tasks (Mauger et al. 2012; Thomas et al. 2012; Tucker et al. 2006a), with most authors speculating that athletes reduce their speed in an anticipatory fashion, in the attempt to prevent the development of excessive disturbances of homeostasis (Abbiss & Laursen 2008; Tucker 2009). A high energy expenditure in the middle of the event might cause premature fatigue and lead to a large reduction in speed before the final portion of the race, hence athletes seem to choose a rather conservative pace in the middle part to 'save energy' for a sprint finish (Thompson 2014). This profile is well known by coaches and athletes and can be observed in a variety of middle- and long-distance events. Surprisingly this pattern has not been well described in research until recently and is in contrast to the previously described *even* pattern, which seems theoretically optimal (de Koning et al. 2011). Contrary to these theoretical assumptions, Thomas et al. (2013) recently observed that nine out of fifteen well-trained cyclists were not able to finish a 20 km cycling time trial when using an even pacing, which was based on the mean power output in a previous self-paced trial. Billat et al. (2006) and Lander et al. (2009) similarly reported that a self-selected pacing resulted in better 10 km running and 5000 m rowing performance compared to an *even* pacing pattern. These results lead to the assumption that self-paced exercise seems to be less physically challenging than *even-paced* exercise and indirectly assume that *even* pacing can have a negative impact on endurance performance. Thomas et al. (2013) speculated that a *parabolic shaped* pattern might result in better performance by optimising the trade-off between maximising intensity and minimising metabolite accumulation to a tolerable level. The characteristics of a *parabolic shaped* pacing pattern might be explained by the kinetics of peripheral and central fatigue during self-paced exercise (Thomas et al. 2014). Studies have shown that the majority of peripheral fatigue occurs in the first half of an exercise bout, with an increasing contribution of central fatigue mechanisms later in the event (Decorte et al. 2012; Froyd et al. 2013). Hence, the reduction in intensity during the middle portion of the event could be attributed to a decrease in the responsiveness of the fatigued motor unit pool to an equivalent efferent command (Thomas et al. 2013). To counteract this decline in power output due to fatigue, the athlete would have to increase central drive, which might result in the recruitment of larger motor units and thus exacerbate the likelihood of premature fatigue (de Koning et al. 2011; Thomas et al. 2013; Thomas et al. 2014). In an attempt to avoid premature fatigue, athletes slow down to manage symptoms of fatigue to a tolerable level.

To conclude current opinion suggests that the ability to vary intensity is an important component of optimal self-paced exercise performance (Billat et al. 2006; Lander et al. 2009; Thomas et al. 2013; Tucker et al. 2006a) and forcing athletes into an even-pacing pattern could be questioned. Improved performance seems to be associated with minor deviations from an *even* pace within a broadly *parabolic shaped* pattern (Billat et al. 2006; Lander et al. 2009; Thomas et al. 2013). It has been reported, that if a starting strategy is too slow in an attempt to preserve metabolic reserves, the power output required later in the race might be too high to sustain (Fukuba & Whipp 1999). Alternatively, starting strategies that are too aggressive result in premature fatigue (Mattern et al. 2001). Future research is warranted to assess the impact of manipulations on pacing, particularly manipulating the starting strategy, to elucidate the optimal pacing pattern for endurance performance.

2.3.6 Variable Pacing

The majority of research on describing ‘optimal’ pacing mentioned so far is predominantely based on trials in controlled laboratory conditions (Atkinson & Brunskill 2000; Foster et al. 2004; Mattern et al. 2001). In real race scenarios wind (de Koning et al. 1999), temperature (Tucker et al. 2006b), course geography (Swain 1997), race tactics and/or opponents (Mauger et al. 2012) lead to varying conditions between and within events. Thus, it has been suggested that a *variable* pacing pattern might be optimal for (endurance) performance (Atkinson & Brunskill 2000; Liedl et al. 1999). The term *variable* pacing has been used to define the fluctuations in exercise intensity observed during an exercise task (Abbiss & Laursen 2008; Atkinson et al. 2007; Liedl et al. 1999). Authors suggest that a *variable* pattern is usually adapted in an attempt to counteract variations in external conditions (Swain 1997) to maintain a constant pace (Abbiss & Laursen 2008) and as such the variable strategy is linked to pervious strategies outlined above. Swain (1997) revealed that modest variations in power output on hilly or windy courses can improve overall cycling performance in 10 km and 40 km time trials. Slightly increasing power on uphill or headwind segments while decreasing power on downhill or tailwind segments produced significant time savings, even though mean power over the segments was held constant (Swain 1997). This finding has been supported by Atkinson & Brunskill (2000) concluding that a variable power results in faster times and lower physiological responses. Despite these findings a few researchers have examined the influence of technique and/or different opponents on pacing pattern (Abbiss &

Laursen 2008; Garland 2005; Mauger et al. 2012; Wilberg & Pratt 1988). Whereas technique might be especially important to pacing in events that experience higher resistive forces (e.g. swimming or rowing) (Thompson 2014), opponent and race tactics might have a high influence in head-to-head races like in running or cycling. Further research is required to better understand the physiological implications of varying power, speed or time in order to determine the possible effect and limitations of a *variable* pacing pattern (Abbiss & Laursen 2008).

To summarize a number of experimental designs as well as observational studies on pacing have been published resulting in a variety of pacing profiles observed during different exercise tasks and under differing conditions. During events of less than 30 seconds it seems that athletes will benefit from a relatively fast start, whereas during more prolonged events a more constant pace might be beneficial (Abbiss & Laursen 2008; Albertus et al. 2005; Ansley et al. 2004; Foster et al. 1993b; Foster et al. 2004; Laursen et al. 2005). During ultra-endurance events of more than 4 hours athletes tend to adopt a positive pacing pattern (Abbiss et al. 2006; Abbiss & Laursen 2008; Laursen et al. 2005; Neumayr et al. 2002). It is likely that differences in pacing observed in varying distances and durations may be related to the rate and capacity limits of various physiological systems (Abbiss & Laursen 2008). Even though it is understood that exercise performance can be significantly influenced by the distribution of intensity during exercise, it continues to be a controversial issue which pattern is most successful in different scenarios.

2.4 Pacing in Swimming

As previously outlined the effect of pacing on performance has received considerable attention in many sports, including cycling (Abbiss et al. 2013; Atkinson & Brunskill 2000; Cangley et al. 2011; Peiffer & Abbiss 2011), running (Bath et al. 2012; Faulkner et al. 2011; Noakes et al. 2009; Tucker et al. 2006a), triathlon (Abbiss et al. 2006; Le Meur et al. 2009; Le Meur et al. 2011), speed skating (Hettinga et al. 2011; Muehlbauer et al. 2010), kayaking (Bishop et al. 2002) and rowing (Garland 2005; Gee et al. 2013; Renfree et al. 2012). However, little attention has been paid to pace selection and swimming. It is noteworthy that observed pacing profiles differ markedly between world-record performances in 200 m front-crawl swimming, 800 m running, and 1500 m speed skating, despite the races' almost identical duration (de Koning et al. 2011; Mytton et al. 2014a). Comparable duration should theoretically result in a similar energetic demand and thus a similar pacing pattern. Within the various sports outlined above the interaction between athletes and thus the influence of competitors differs a lot. Pool swimming races are performed in separate lanes for the entire race, whereas runners will come into closer contact possibly leading to a greater tactical influence. Furthermore, the resistive forces are higher in swimming (Maglischo 1993; Smith et al. 2002) and thus a direct transfer of results from land-based endurance sports is not possible. As with all models of locomotion, fluid (frontal-water) resistance increases disproportionally with increasing velocity (Batchelor 1967; Maglischo 1993), however within swimming this results in a considerable rise in energy expenditure with increasing swimming speed (Foster et al. 1994; Mauger et al. 2012). Swimming is mechanically inefficient, since only 6% to 18% of the energy created by the metabolism is converted into muscle work (Holmer 1974; Pendergast et al. 1979 as quoted by; Thompson 2014). Furthermore, any minor alterations in speed during swimming is likely to have considerable influence on performance, which is perhaps more significant than in other land-based sports.

Reducing frontal water resistance by developing a streamline body position is seen as a crucial factor in swimming performance. Fatigue during swimming typically results in a deeper in-water position and an increased breath frequency (e.g. every stroke rather than every 2nd stroke) both of which negatively effects the streamlined body position leading to a higher drag (Thompson 2014). Altogether this can end in a vicious circle as the swimmer gets more fatigued: swimming technique deteriorates, leading to higher resistance, increased energy cost, and ultimately even greater accumulation of fatigue (Thompson 2014). With this in mind, appropriate pacing in swimming is likely to have considerable effects on performance as a result of this rapid onset of fatigue which causes loss of stroke power, coordination and speed (Thompson 2014). Conversely, less frequent changes in speed may reduce energy cost needed to overcome drag and improve swimming performance (Mauger et al. 2012; Thompson 2014). Mytton et al. (2014b) recently compared running and swimming events of a similar duration (1500 m run vs. 400 m swim; ~4 min) observing a greater variation in lap speed during the running race compared to the swimming event, most likely due to the lesser influence of opponents and the greater drag forces in the water. In contrast to land-based sports it seems that an even pattern with an initial fast start (due to the start dive) may be more appropriate (Mauger et al. 2012). Besides the mechanical inefficiency and the increased drag a theoretically optimal pacing pattern in swimming might further differ according to the stroke and/or the distance.

2.4.1 Biomechanics of Different Strokes

Choosing the most appropriate pacing in swimming is a complex decision, because athletes may compete in up to four swimming strokes over varying distances, possibly requiring the adaptation of different patterns (Thompson 2014). These events include:

- Freestyle or front-crawl:	50 m to 1500 m in the pool and over 5 km in the open water
- Butterfly:	50, 100, 200 m
- Backstroke:	50, 100, 200 m
- Breaststroke:	50, 100, 200 m

In the individual medley swimmers even have to perform all four strokes within one race (100 or 200 m). In this regard it is noteworthy that each stroke has its own mechanical efficiency that influences energy cost and the development of fatigue throughout the race. Breaststroke is the least efficient stroke, whereas front-crawl is the most efficient (Holmer 1974). When swimming at the same speed breaststroke requires an additional 1.2 litres of oxygen compared to front-crawl, mainly due to higher fluctuations in velocity within one stroke cycle (Holmer 1974) (Figure 13).

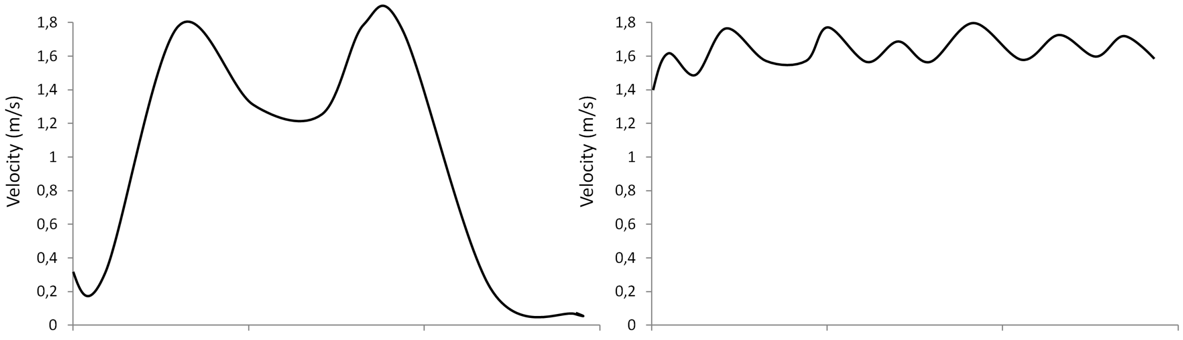

Figure 13 Velocity pattern during one stroke cycle in breaststroke (left panel) and front-crawl (right panel, two cycles) (replicated from Barbosa et al. 2011).

As displayed in figure 13 intra-cyclical peak velocities in breaststroke are comparable to front-crawl, however, speed decreases substantially during the recovery phase. The need to accelerate during each stroke contributes to the relative inefficiency of breaststroke and results in a higher energetic demand (Thompson 2014). Butterfly is also less efficient than front-crawl or backstroke. Craig & Pendergast (1979) calculated that a 45 to 50% change in race-speed occurred during butterfly and breaststroke events compared to only 15 to 20% difference in front-crawl and backstroke races. Indeed, lap times during 200 m front-crawl races decrease approximately 0.4 s from lap two to four, whereas in breaststroke and butterfly a difference of up to 1.2 s has been observed (Robertson et al. 2009). This might be partly due to fatigue related changes in stroke rate and stroke length, since swimming speed can be calculated as follows (Smith et al. 2002):

$$Speed = stroke\ rate \times stroke\ length$$

Throughout an event swimmers usually increase speed by a combination of increasing stroke length and/or stroke rate (Smith et al. 2002), hence both factors need to be considered when optimizing performance (Aspenes & Karlsen 2012). However, stroke length seems the more critical factor in achieving best performance (Smith et al. 2002). A stroke efficiency index can be calculated by multiplying swimming speed per stroke length assuming the swimmer who moves the greatest distance per stroke has the most efficient technique (Smith et al. 2002). As the race progresses a swimmers stroke efficiency index progressively decreases, most likely due to an increase in stroke rate and a decrease in stroke length (Smith et al. 2002). The decreasing stroke rate consequently reduces the potential for propulsion resulting in a lower velocity. Ultimately, such a change in mechanics reduces swimming economy and leads to a higher energy expenditure. Inevitably, this results in an earlier development of fatigue and, thus changes in pacing. In the short-term (within a race) a swimmer should strive to increase stroke rate while maintaining stroke length and thus increasing or at least maintaining speed (Smith et al. 2002). Increasing the stroke rate during a race seems to be more problematic in butterfly and breaststroke. For example, Thompson & Haljand (2000) found that stroke length significantly deteriorated on each subsequent 50 m during 100 m and 200 m breaststroke races, indicating increasing fatigue. Although swimmers attempted to compensate the decreasing stroke length by increasing stroke rate this proved to be insufficient and inefficient since swimming velocity still dropped (Thompson et al. 2000). The strategy of increasing stroke rate throughout a race to compensate for a reduced stroke length is common, however, it seems most effective for maintaining swimming speed in the crawl strokes (Chengalur & Brown 1992; Kennedy et al. 1990; Wakayoshi et al. 1992). It seems that front-crawl swimmers have a higher range to compensate for a loss in stroke length by increasing stroke rate to a greater extent (Thompson 2014). To summarize, the initial pace a swimmer adopts early in a race may be more critical in butterfly and breaststroke events due to the relative inefficiency of these strokes and because changing the pace during the race seems much more feasible than in front-crawl and backstroke (Thompson 2014).

2.4.2 Physiology and Pacing in Middle-Distance Swimming

Maglischo (1993) reported that in 100 m events swimmers pace positively (fast start, slower finish), whereas in the 200 and 400 m events a more evenly pacing strategy is chosen (Figure 14). More recently, Mauger et al. (2012) observed that elite swimmers favour fast-start-even and parabolic-shaped pacing profiles during 400 m front-crawl competitions. However, no single pacing pattern appeared to exert a significant influence on overall performance time (Mauger et al. 2012). Nonetheless taking into account that the difference between medallists at international-level is around 1%, the observed performance difference of 1.7 s could be meaningful and emphasizes the importance of pacing (Mauger et al. 2012). For pool events longer than 400 m an even pacing has generally been observed (Thompson 2014). As aforementioned the different strokes might require different pacing patterns due to their biomechanics. In this regard, Thompson & Haljand (2000) observed that mid-pool swimming velocity (velocity without the start dive and the turns) significantly decreases over each consecutive 50 m during the 100 m as well as the 200 m breaststroke event, resulting in a positive pacing pattern.

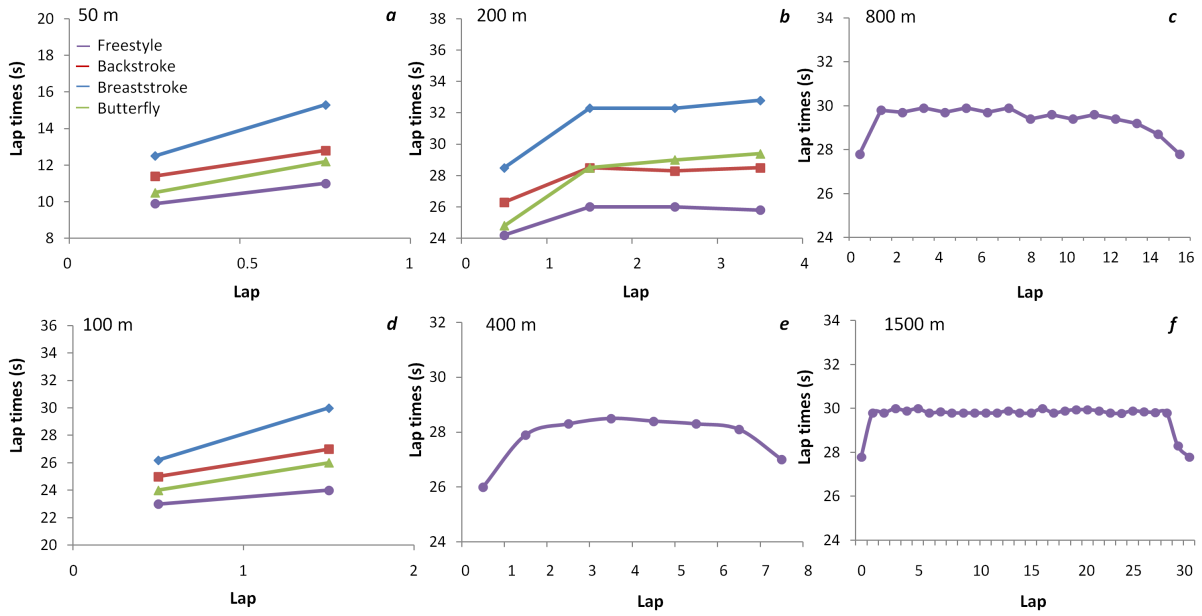

Figure 14 Pacing in swimming across various distances and strokes (replicated from Thompson 2014)

As displayed in panel **a**, ***b*** and **d** in figure 14 breaststroke and butterfly show the greatest loss in speed throughout a race. Whether this decrease in velocity is optional is currently unknown. Regardless the figures above highlight that coaches and athletes are required to choose the right pacing pattern for each event and individual swimmer, since even small changes in racing speed might have a marked effect on the swimmer's physiology (Thompson 2014).

Robertson et al. (2009) analysed international level swimmers during real competitions observing that front-crawl swimmers tend to adopt similar pacing patterns in 100, 200 and 400 m races from one event to the next. This is in accordance with several studies showing consistent pacing patterns in 4 km cycling (Stone et al. 2011) and rowing (Gee et al. 2013). As previously described several pacing models acknowledge the importance of prior experience on the distribution of exercise intensity (Pageaux 2014; St Clair Gibson & Noakes 2004; Tucker 2009). Therefore, elite swimmers might develop a robust pacing template, which seems to be stored in the long-term memory and is most likely based on several previous competitions. Interestingly, Robertson and colleagues (2009) drew the conclusion that pacing only has minor effects on the final ranking in a certain event, since the observed pacing pattern was similar between swimmers and competitions. They argue that the overall fitness has to be improved to achieve faster lap times and thus better performance (Robertson et al. 2009). However, taken into account that the difference between medallists in swimming is < 1% (Pyne et al. 2004) optimisation of pacing when the swimmer's fitness improves might have a further meaningful effect.

In an attempt to optimize performance a number of studies have examined the influence of external pacing manipulation on exercise performance, with conflicting results (Aisbett et al. 2009; Foster et al. 1993b; Foster et al. 1994; Gosztyla et al. 2006; Mattern et al. 2001). Only a few studies have looked specifically at the effect of manipulating pace during swimming. An early study by Swaine and Reilly (1983) found significant changes in oxygen uptake and minute ventilation when stroke rate was manipulated during high-intensity front-crawl swimming. However, the authors evaluated simulated swimming on a swim bench rather than actual performance in the pool. A later study also manipulated stroke rate during 200 m breaststroke swimming. Using a programmable audible pacing device swimmers were paced at 92%, 95%, 100% and 107% of their average stroke rate in a previous self-paced trial, yet no statistical significance between trials was observed in performance times, physiological responses and RPE (Thompson 2014). In another breaststroke study, swimmers completed a total of four 200 m trials, in which the first one was swum with a self-selected pace (Thompson et al. 2004). After that swimmers had to complete three additional trials in a random order at 98%, 100% and 102% of their average velocity in the self-selected trial (Thompson et al. 2004). Pacing manipulation resulted in an even pattern when swimming at 98% and 100%, whereas the 102% was swum with a positive pattern (Thompson et al. 2004). The authors further observed comparable physiological responses in the evenly paced races. However, the positive trial resulted in elevated blood lactate and higher respiratory exchange ratio assuming a greater anaerobic energy contribution. Heart rate and oxygen consumption were comparable in all three trials indicating similar aerobic energy cost. Despite the higher demand of anaerobic pathways, the positively paced trial resulted in a 0.8% better performance time (Thompson et al. 2004). However, swimmers also reported greater RPE values assuming that mental toughness might be more important when swimming with such a strategy (Thompson et al. 2004). In another study the same authors asked swimmers to complete 175 m breaststroke with an even (average speed of a pervious self-selected trial), positive (2% faster in the first 100 m, 2% slower in the second 100 m) and a negative pacing (2% slower in the first 100 m, 2% faster in the second 100 m) (Thompson et al. 2003). Again, aerobic energy contribution was comparable in all the trials yet, the even-pace trial resulted in lower blood lactate levels and RPE values suggesting a less stressful response compared to a positive or negative pacing pattern (Thompson et al. 2003). Additionally, overall performance was impaired when participants started faster, which is most likely associated with an early development of muscle fatigue (Thompson et al. 2003). Considering these results it seems surprising that in real race observations a positive pacing is the most common pattern in breaststroke swimmers (Thompson 2014).

2.4.3 Pacing in Simulated and Real Swim Competitions

If prior experience is an important factor within intensity regulation it could be assumed that younger, less experienced swimmers might not have a stable pacing template. Micklewright et al. (2012) recently observed differences in pacing between schoolchildren at different age and cognitive development. Younger children whom were less cognitively developed exhibited a negative pacing pattern in a 4 min running time trial whereas older children at a more advanced stage showed a more even pacing template (4 - 5 y = 450 m, 8 - 9 y = 600 m, 11 - 12 y = 750 m, and 14 y = 900 m). The authors hypothesized that younger children seem to be less able to anticipate the demands of the exercise and that the ability to self-select an appropriate pace needs to develop during childhood and might partly be contingent upon intellectual development (Micklewright et al. 2012). Considering that swimmers become professional at a young age compared to other endurance sports (average age at the 2012 Olympics: swimming: 23 y; marathon: 29 y) optimising pacing in early years during (simulated) training competitions might be advantageous. Yet it is unknown if swimmers choose the same pacing pattern in training and competition. The majority of pacing studies have been conducted under standardized laboratory conditions. However, in real competitions, race tactics, opponents, environmental conditions (Abbiss & Laursen 2008; Mauger et al. 2012) as well as competition induce changes in cardiovascular and respiratory parameters (Viru et al. 2010) might influence the overall pacing pattern (Abbiss & Laursen 2008; St Gibson et al. 2006). Thus, a better understanding of the transferability from simulated to real completion would be desirable especially since it is still unclear if observed pacing profiles are optimal for best performance in each individual swimmer. Further knowledge on the variability of pacing in simulated and real swimming events would be desirable to determine if overall performance enhancements or impairments are a result of (external) pacing manipulations or part of the 'normal' day-to-day variation. Since environmental conditions are nearly constant in swim training and competition it can be suggested that such simulated trials might be a useful model for pacing research in swimming. Furthermore, swimmers seem to be more ‘isolated’ from their opponents compared to other endurance sports. Mytton et al. (2014b) proposed that since runners are competing in the same lane they are more concerned about tactical considerations (Renfree et al. 2014b), drafting benefits (Brownlie et al. 1987) and their opponents pace, whereas swimmers are less spatially affected by their opponents and are able to adopt a more consistent race pattern (Mytton et al. 2014a; Mytton et al. 2014b).

To summarize, even though pacing research has increased tremendously over the last decade limited data has been published in regards to swimming. Swimmers preferably self-select a fast-start even or parabolic shaped pacing pattern in the crawl strokes (Mauger et al. 2012), whereas breaststroke and butterfly swimmers seem to pace more positively (Maglischo 1993; Thompson 2014), most likely due to swimming mechanics of the strokes. Elite swimmers seem to develop a robust pacing template over their career, which is consistent from one race to the next (Robertson et al. 2009). However, since the majority of these studies analysed elite swimmers in national and international competitions (Maglischo 1993; Mauger et al. 2012; Pyne et al. 2004; Robertson et al. 2009) data on pacing in highly-trained junior swimmers is still missing. Considering that the pacing template seems to be stored in the long-term memory and recalled for events of similar duration or distance, knowledge on pacing in a younger cohort might be crucial to develop an optimal pacing at an early stage. That said it is still unclear if those observed pacing patterns represent the optimal race plan for the individual swimmer. Thompson et al. (2003; 2004) observed greater physiological stress and a decreased performance when swimmers paced positively during 200 m breaststroke, nonetheless it seems to be the favoured pattern in real races (Thompson 2014). Additionally, to the author’s knowledge no studies have yet observed the effects of pacing manipulation in other strokes and/or greater distances.

Therefore, the aim of this thesis is to examine the variability within the pacing profile of highly-trained junior and world-class swimmers and analyse the influence of pacing manipulation on overall swimming performance. Specifically, **Study 1** aimed to establish the variability of pacing in middle-distance front-crawl events (200 m to 800 m) during simulated competitions in highly-trained junior swimmers. Additionally, pacing was compared to real race scenarios to establish if such simulations can be used as a tool for pacing research and training. Following this, the pacing of world-class swimmers was examined to determine if consistent pacing patterns exist between (one event to the next) and within (heat to final race) real competitions as well as in different strokes and distances (**Study 2**). Finally, the aim of

Study 3 was to manipulate the initial section during 400 m front-crawl simulated competitions in contrast to a self-selected race pace, to analyse possible effects on overall performance, as well as on the pacing pattern during the later sections. A better knowledge of swimmer's day-to-day variation in pacing would help sport scientists and coaches when calculating the smallest worthwhile change (Hopkins 2000), which would presumably lead to a better understanding whether a meaningful change in performance occurs. Furthermore, greater insight into the effects of pacing manipulation would provide a better understanding about methods and techniques with which to best prepare swimmers for competition and thus reach optimal performance levels.

3 Study Overview

Study 1

3.1 Reproducibility of Pacing Profiles in Competitive Swimmers

Skorski S, Faude O, Rausch K, Meyer T

International Journal of Sports Medicine 2013; 34(2): 152 – 157.

Introduction: This study aimed at determining the reproducibility of pacing profiles during simulated swimming trials as well as the comparison between simulated and real competitions in highly-trained junior swimmers. **Methods:** Sixteen competitive front-crawl swimmers (7 females, 9 males) performed a 200 m, 400 m and 800 m trial twice within one week (test and retest). All 100 m split and total times were recorded for the 400 m and 800 m bouts, additionally 50 m split times were measured for the 200 m trail. For each distance the pacing pattern of one real competition within a maximum of eight weeks before or after data acquisition was used for comparison to the simulated trial. A two-way repeated measures ANOVA was used to test for global effects between test and retest as well as between real and simulated competition. Standard error of measurement (SEM) and log-transformed coefficient of variation (CV; 90% Cl) were calculated to estimate within-subject variation for each section and for overall performance. **Results:** No difference was observed between test and retest for overall performance ($p < 0.16$). CVs for all split times during 800 m were between 0.9 and 1.8% (SEM: 0.6 – 2.1 s), except for the last 2 sections (CV: 2.5 and 2.9%). During 400 m and 200 m, the CV was below 1.7% for each section (SEM: 0.4 – 1.7 s). Absolute mean differences between test and retest ranged from 1.8 s (Cl: 0.1 – 3.4 s) in the 400 m bouts to 4.1 s (Cl: 1.3 – 9.5 s) for the 800 m races. Absolute section times were faster in all splits during the real competition ($p < 0.001$); yet pacing pattern was not significantly different compared to the simulated trial ($p > 0.22$). **Discussion**: In conclusion, the hypothesis that athletes develop a stable pacing pattern has been particularly confirmed for the first three quarters of the race. The last quarter showed greater absolute variability for each distance. This leads to the assumption that anticipatory control and prior experience might be dominant at the beginning and in the middle of the race, whereas actual sensory feedback becomes more important during the final spurt. Furthermore, simulated trials seem to be an acceptable model to analyse pacing in competitive swimming.

Study 2

3.2 Reproducibility of Pacing Profiles in Elite Swimmers

Skorski S, Faude O, Caviezel S, Meyer T

International Journal of Sports Physiology and Performance 2014; 9(2): 217 – 225.

Introduction: Pacing pattern seems to be stable at the beginning of middle distance simulated swimming competitions in highly-trained junior swimmers. Taking into consideration that prior experience has an influence on pacing it is unsure if these results can be transferred to elite swimmers. Hence, the aim of this study was to analyse the reliability of pacing between competitions in world-class swimmers and to examine possible differences between heats and finals within the same competition. **Methods**: Finals and heats of 158 male swimmers (age 22.8 ± 2.9 y) from 29 nations were analysed in two competitions on average 7.7 ± 5.4 weeks apart. Of these, 134 swimmers were listed in the world's top 50 in 2010; the remaining 24 were finalists of the Pan Pacific Games or European Championships. The level of both competitions for the analysis had to be at least national championships. Total and 50 m split times for all 200 m front-crawl, butterfly, backstroke and breaststroke events as well as for the 400 m front-crawl race were downloaded from the official site swimrankings.net. Standard error of measurement expressed as percentage of the subject's mean score (CV) with 90% Cl for each 50 m split time and for total times were calculated. In addition, mixed general modelling was used to determine standard deviations between and within swimmers. **Results**: CV for total time in finals ranged between 0.8% and 1.3% (Cl: 0.6 – 2.2%). Regarding 50 m times, 200 m front-crawl showed a consistent pacing over all split times (CV: 0.9 – 1.6%). During butterfly, backstroke, and 400 m front-crawl, CVs were low in the first three and seven sections, respectively (CV: 0.9 – 1.7%), with greater variability in the last section (CV: 1.9 – 2.2%). In breaststroke, values were higher for all split times (CV: 1.2 – 2.3%). Within-subject standard deviations for changes between laps were between 0.9% and 2.6% in all final races. When comparing finals and heats split-time variability ranged between 0.9% and 2.5% (Cl: 0.3 – 4.9%). **Discussion**: Elite swimmers seem to develop a stable pacing pattern in their career, resulting in low variability between different competitions and within one event. Occurring variations in the pattern seem to be

related to the swimmer himself rather than to different competitors or competitions. Based on the current results it can be suspected that a change in the pacing template needs training and competition experience to store the pattern in the long-term memory and change the program in the motor cortex.

Study 3

3.3 *Influence of Pacing Manipulation on Performance of Juniors in Simulated 400-m Swim Competitions*

Skorski S, Faude, O, Abbiss CR, Caviezel S, Wengert N, Meyer T

International Journal of Sports Physiology and Performance 2014; 9(5): 817 – 824.

Introduction: The impact of manipulating the starting strategy on race performance and pacing is still equivocal. A number of studies have demonstrated a positive effect of a fast-start pacing on short- and middle distance endurance events, yet mostly under standardised laboratory conditions. Further research is warranted to understand the influence of starting strategy in actual race scenarios. As such, the purpose of the current study was to examine the influence of pacing manipulation on 400 m front-crawl swimming performance. **Methods**: 15 front-crawl swimmers (5 female, 10 male; age 18 ± 2 y) performed three simulated 400 m swimming events. During the first trial participants were free to self-select their pacing pattern (PP_{SS}). In the following two visits they were required to complete the first 100 m of the event using a fast- (PP_{FAST}: 4.5% ± 2.2%) or a slow-start (PP_{SLOW}: 2.4% ± 1.6%). All 50 m split times and overall performance times were recorded during each trial. A one-way repeated measures ANOVA was performed to examine differences between final times. For the comparison of pacing and stroke rate between trials, a two-way ANOVA was performed. **Results**: Overall performance time was faster in PP_{SS} (275.0 ± 15.9 s) compares to PP_{FAST} (278.5 ± 16.4 s, $p = 0.05$) but not significantly different to PP_{SLOW} (277.5 ± 16.2 s, $p = 0.22$). Analysis for practical relevance revealed that manipulations of the starting strategy resulted in a “likely” (> 88.2%) relevant decrease in performance compared with PP_{SS}. However, seven of the 15 swimmers recorded their fastest time during a manipulated race (three in PP_{FAST}, four in PP_{SLOW}). On average, swimmers were 0.6% (0.1 – 1.4%) faster than in PP_{SS}. **Discussion:** A moderate manipulation of the starting speed during simulated 400 m front-crawl races seems to affect overall performance. It also appears that some swimmers may not have self-selected an optimal pacing pattern, since their performance was better in a manipulated race. Well-trained swimmers could therefore benefit from trying and practicing new pacing profiles during training or even real competition. Further research should focus on the identification of the athletes who might profit from pacing manipulations.

4 Summary of Findings

The results of the studies conducted within this thesis indicate that high-level junior swimmers can perform middle-distance simulated competitions with good reproducibility. World-class swimmers further seem to develop a stable pacing pattern over the span of their career, which is consistent within the same event and from one competition to the next. Thus, elite swimmers might not change their ‘race plan’ according to different competitors and/or different events. However, it remains unclear if an athletes’ self-selected pacing is optimal for their best performance since (external) manipulation of the starting strategy improved 400 m front-crawl performance in a considerable number of swimmers.

The theoretical assumption that pacing profiles are stable has been confirmed, particularly for the first three quarters within the simulated competitions. The last quarter, however, showed greater absolute variability. This leads to the hypothesis that anticipatory control and prior experience might be dominant during the initial phase of the race, whereas actual sensory feedback becomes more important during the final sprint. Variability in elite swimmers was even smaller from one competition to the next as well as within one event. Since variation was greater within-subjects compared to between-subjects, variability seems to be related to the swimmer himself rather than to different competitors or competitions. From a practical perspective, the described variation (0.8 to 1.3%) is low enough to detect a worthwhile change in performance in high-level swimmers. Furthermore, simulated trials seem to be an acceptable model to analyse pacing in competitive swimming in the future. Whether the chosen pacing pattern is optimal for each individual swimmer remains still unclear. The results of **Study 3** indicated that some swimmers do not self-select an optimal pacing, since their performance was better in a manipulated race. Thus, the current results demonstrate, that individual swimmers could benefit from experimenting with small variations in pacing around the theoretical optimum provided by models to find the individual pattern that works best under specific conditions (de Koning et al. 1999). Considering that performance of gold, silver and bronze medalists are within 1% of each other practicing new pacing templates might be of great importance for success. This might be especially true for swimming taking into account, that energy expenditure increases to a greater extend when intensity rises compared to other endurance sports (Maglischo 1993). Only slight variations in pacing might have a large influence on overall performance outcome. However, based on the current findings it can be suspected that a change in the pacing template generally needs training and competition experience to store the pattern in the long-term memory and change the program in the motor cortex (Mauger et al. 2009; St Clair Gibson et al. 2001a). As such, results from this thesis may aid sports scientists, athletes and coaches in better understanding methods and techniques by which to best prepare swimmers for competition.

Surprisingly, athletes and coaches rarely experiment with pacing, especially not in real competitions, most likely due to fear of failure. From a scientific perspective future research should aim at a better understanding what constitutes optimal pacing for each individual and identify those athletes who might profit from pacing manipulations. In this regard, sport scientists should not only focus on physiological variables possibly indicating ‘optimal’ pacing for an individual but also include psychological factors such as personality aspects, affect, focus, emotions and motivation (Jones et al. 2013). A recent review by St Clair Gibson et al. (2013) proposed that psychological drives and physical homeostasis are internally competitive requirements. A particular pacing pattern needs to be defined in a way to satisfy either or both of these conflicting requirements. As such ego-orientated athletes, who are driven to defeat competitors, and task-orientated athletes, who are more focused on self-improvement (Decci & Ryan 1985; Nicholls 1984), may (consciously or subconsciously) choose a different pacing pattern to satisfy their motivational drives. Furthermore, Renfree et al. (2014a) recognize that human behavior in general occurs as a result of both the situation and the person. In the same situation different athletes may make unique choices which might be linked to goal setting, motivation and/or affect (Renfree et al. 2014a). How the psychological drive interacts with the physical system is not clear and warrants future research combining both.

It continues to be a controversial issue what mechanisms constitute pacing during different exercise tasks. Interestingly none of the current models can explains why athletes ‘choose’ a unsustainable intensity at the beginning of a race leading to a collapse before the finish line, or else, start off too conservative and hence finish with a large final sprint. If homeostasis is continuously monitored through a central regulator, the athlete should ‘decide’ to adjust intensity earlier through the race to prevent these occurrences. One of the issues causing major debates between researchers is the question if pacing is regulated consciously, subconsciously or on different levels of awareness. Taking into account that a central aspect within many of the proposed models is the participants’ perception of exertion, perception of effort and the task demands (de Koning et al. 2011; Marcora 2009; Pageaux 2014; Tucker & Noakes 2009) it should be considered, that intensity regulation might be influenced by (the awareness of) both conscious sensations of fatigue and subconscious sensory feedback from physiological systems.

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“Persistence can change failure into extraordinary achievement.”

- Matt Bondi

Appendix

The appendix includes the original manuscripts in the following order:

1. Reproducibility of Pacing Profiles in Competitive Swimmers. Skorski S, Faude O, Rausch K, Meyer T. International Journal of Sports Medicine.

2. Reproducibility of Competition Pacing Profiles in Elite Swimmers. Skorski S, Faude O, Caviezel S, Meyer T. International Journal of Sports Physiology and Performance.

3. Influence of Pacing Manipulation on Performance of Juniors in Simulated 400-m Swim Competition. Skorski S, Faude O, Abbiss CR, Caviezel S, Wengert N, Meyer T. International Journal of Sports Physiology and Performance.

Reproducibility of Pacing Profiles in competitive Swimmers

Original Investigation

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Short title: Reproducibility of Pacing Profiles

Original Investigation

Text character count : 19.834
Figures : 3
Tables : 2

Abstract

This study aimed at determining the reproducibility of pacing profiles (PP) during simulated swimming trials as well as the comparison between simulated and real competitions (RC). Sixteen competitive front crawl swimmers (7 females, 9 males) performed 2x200m, 2x400m and 2x800m tests, each test 7 days apart. All 100m split (ST) and total times (TT) were recorded (additionally 50m ST for the 200m bouts). The PP of one RC within a maximum of 8 weeks before or after data acquisition was used for comparison. No difference was observed between test and retest for TT ($p<0.16$). Coefficients of variation (CV) for all ST during 800 m were between 0.9 and 1.8% (standard error of measurement (SEM)=0.6-2.1s), except for the last two sections (CV=2.5% and 2.9%). During 400m and 200m, CV was below 1.7% for each section (SEM=0.4-1.7s). Mean differences between test and retest ranged from 1.8s (CI: 0.1-3.4s) in the 400m bouts to 4.1s (CI: 1.3-9.5s) for the 800m races. Although section times were faster during all sections of RC compared to SC, PP was similar during both trials ($p>0.22$). However, swimmers were faster in each section during RC. In conclusion, PP seem stable, at least during the first three quarters of the race. Furthermore, simulated trials seem to be an acceptable model to analyse PP in competitive swimming.

Introduction

During the last decade research on pacing profiles has gained considerable attention in exercise physiology, due to the belief that pacing has a major effect on performance in many endurance disciplines [1, 13]. During competition athletes try to choose their optimal "strategy" to use all possible energy stores before finishing the race but not so far from the end that a meaningful slowdown occurs [30]. It is speculated that the regulation of exercise work rate is achieved by a combination of feedback integration, anticipatory forecasting and previous experience [21, 29, 30]. Furthermore, it is assumed that after a particular competition, the pacing profile is used as a schema for bouts of the same race distances in future events [20]. It is unknown whether the individually chosen profiles represent the optimal scenarios [1] and whether pacing patterns can be adapted as a result of training and competitive experience [1, 7, 12].

To analyze training or maturation induced changes, it is important to establish the usefulness of a test by calculating the smallest worthwhile change within tests and/or competitions, to distinguish whether real changes have occurred after interventions [16, 27, 28]. Most data on reproducibility focus on overall performance in self-paced tests [18, 23, 24]. Few studies have looked at the pacing pattern during repeated exercise trials [2, 10]. Stone et al. [27] found a coefficient of variation (CV) of 5 to 10% at the beginning and the end of cycling time trials, but only about 2% in the middle. To our knowledge scientific data on test-retest-reliability of pacing profiles are only available for well-trained cyclists [27, 28]. Results in well-trained swimmers are missing so far.

Most of the described data were conducted under standardized laboratory conditions, which are difficult to transfer directly into real competitions. Competition situations can induce anticipatory changes in cardiovascular and respiratory parameters [33] which may change pacing [1, 25]. It is not known, if athletes actually choose the same pacing pattern in real competition compared to training. A better understanding of the transferability from simulated to real competition would be desirable [11]. Brown et al. [6] showed that rowers adapt different profiles during ergometer and on-water races. Thus, environmental influences can have a notable influence during rowing or cycling. Tough Chatard et al. [8] showed that water disturbances can influence swimming performance, the environmental conditions are nearly constant in swim training and competition. It can be suggested that simulated trials during training might be a useful model of pacing profiles in real competition.

The aim of the present study was to analyze the reproducibility of pacing profiles in high-level junior swimmers during 200, 400 and 800m simulated competitions and to calculate the smallest worthwhile change in both overall performance, and pacing pattern. Furthermore, pacing profiles during simulated and real competitions were compared to evaluate whether simulated competitions can be a useful tool for training interventions.

Methods

Subjects

Sixteen competitive front crawl swimmers (7 females, 9 males; age: 16.9±2.1 y, 1.77±0.09 m, 65.7±10.4 kg, training amount: 34.7±5.6 km/week) participated in the study. Athletes were of regional to national level and specialised between 100 and 800m. Each athlete was fully informed about the risks and stresses associated with study participation and gave his/her written informed consent before the start of the study. If participants were under 18 years old, written informed consent was also obtained from their parents. All procedures are in accordance with the ethical standards of the IJSM [14] and the Declaration of Helsinki and were approved by the local ethics committee (Ärztekammer des Saarlandes, Saarbrücken, Germany).

Study Design

Each athlete completed six simulated swimming competitions (SC): 2x200m ($200_{test}/200_{retest}$), 2x400m ($400_{test}/400_{retest}$) and 2x800m ($800_{test}/800_{retest}$). All single SC were separated by 7 to 9 days. . Due to external training camps (n=1) or illness (n=4) it was not possible for all swimmers to complete all six tests. This resulted in different numbers of athletes (800m: N=16, 400m: N=14, 200m: N=11) remaining for analysis. Real competitions (RC) during 8 weeks before or after data acquisition were analysed for every athlete. Due to distance specifications it was not possible to analyze competitions for all distances in some athletes. This also resulted in different numbers of swimmers remaining for the comparison of SC and RC (800m: N=11, 400 m: N=13 and 200m: N=12).

Simulated competitions

During all tests 100m split times were measured using handheld stop-watches. Split times were measured when swimmers touched the wall during the turn with their feet, total times (TT) when they touched it finally with the hand. The same investigators measured times for the same swimmers during each test. Additionally, 50m split times were measured during the 200m trials. Capillary whole-blood samples (20 µl) were taken from the hyperemized earlob immediately after the test, and 1, 3, 5, 7, 9 and 11 min after cessation of exercise and analyzed for peak blood lactate concentrations (bLa, automated enzymatic-amperometric method, Greiner BioChemica, Flacht, Germany). Heart rate (HR) (Polar Electro, Kempele, Finnland) was measured after each test. Swimmers avoided stressful training during the day before the test (controlled by the daily training diary). Athletes were advised to maintain their diet similar 24 hours prior to each test. This was controlled by means of written protocols. All tests were organized as competitions and swum in front-crawl. Each swimmer performed an individual warm-up, which consisted of low- to moderate-intensity aerobic swimming (~1000m). The swimmers were advised to repeat the same warm-up before each trial of the same distance. As lane position and water disturbances can influence performance and pacing, SC were organized to resemble RC as closely as possible. Participants were classified into different groups by their personal best time (taken out of competitions close to the tests). In each group were 2 to 3 athletes. Each swimmer raced against the same opponent(s) in the same swimming lane for both trials of one distance. Participants were instructed to complete the distance as fast as possible. Females completed the tests in normal swim suits, males were allowed to wear trunks up to the knee (according to FINA Swimming rules, 2010). To minimise diurnal variations all tests were conducted at the same time of the day in a 50m indoor swimming pool (26°C).

Real competitions

For the comparison with SC, official competitions before or after data acquisition (on average 26 days) were evaluated, using the website swimrankings.net, which is based on information from the German (DSV) and European Swimming Federations (LEN). For the 200m test only the two 100m sections were compared, because it was not possible to get 50m split time during RC.

Statistical analysis

Data are presented as means with standard deviations (SD). A two-way repeated measures ANOVA (factor 1: test; factor 2: section of the test) was used to test for global effects between test and retest as well as between SC (retests used for analysis) and RC. Cohen´s d was calculated as an estimate of practical relevance for the differences in total performance time between RC and SC. Within-subject-variation for each section as well as for total times were calculated by means of the standard error of measurement (SEM) and the log-transformed CV (with 90% confidence intervals (CI)). According to previous findings on between-competition consistency of swimming performance in swimmers of a similar performance level a CV of about 1.5% was assumed acceptable for total times [26]. For the analyses of the pacing pattern, velocity for each 100m section was expressed relative to the average velocity of the whole trial. Bland-Altman plots were used to evaluate, whether there was any heteroscedasticity in the data, i. e. whether the amount of within-subject variation was dependent on performance time [3].

Results

Total time, bLa_{end} and HR_{end} in test and retest were not significantly different ($p>0.13$, table 1). Mean differences between test and retest ranged from 1.8s (CI: 0.1-3.4s) in the 400m bouts to 4.1s (CI: 1.3-9.5s) for the 800m races. A significant gender difference was observed for the normalized profiles of male and female swimmers during both 800m ($p<0.01$ each), as well as the first 400m test ($p=0.02$), with a higher decrease of velocity after the start in females. The observed differences had no effect on reproducibility and, thus, male and females were analysed together in this regard.

With regard to pacing pattern, athletes adopted a fast-start profile with a significantly faster first section in each trial during SC (figure 1, $p<0.002$) and RC (figure 2, $p<0.001$). CV with 90% CI for total time as well as for every section between test and retest as well as SEM (with 90% CI) for SC and RC are shown in table 2. CV for test-retest was small for the first three sections (CV<2.0%, for the first six sections in 800m) and increased towards the end of the simulated races. Regarding SC and RC mean differences in overall performance for male subjects ranged from 2.4s (CI: 1.3-6.1s) in the 200m bouts to 5.8s (CI: 1.8-12.8s) for the 800 m races, whereas in female athletes mean difference was between 1.4s (CI: 3.1-5.9s) in the 200m trial and 26.7s (CI: 9.3-44.1s) in the 800m race. PP was similar in SC and RC ($p>0.22$, figure 2). Similarly, there was also no significantly different pacing pattern for absolute velocities between SC and RC (ANOVA interaction effect: $p > 0.10$ data not presented), despite consistently faster section times during RC (ANOVA test effect: $p < 0.001$). SEM for intra-individual differences in split times between SC and RC were small in the middle of the race during 800m (second to sixth section) and 400m (sections 2 and 3, SEM<1.6s) The first section showed higher SEM in both distances (>1.8s). Furthermore, the last section during 400m and the last two sections during 800m showed higher SEM (>1.8s). As Bland-Altman plots do not indicate any heteroscedasticity in the data, within-subject variation was not dependent on overall performance time (figure 3). The same was true for all split times (data not presented).

Discussion

This study demonstrated that pacing pattern during SC in young swimmers is consistent during the first three quarters of the race in all investigated distances (CV<2%). However, the absolute variability in split times during the last quarters was higher (CV=2.2–2.9%). These data therefore suggest that a stable pacing pattern [4, 15, 19] cannot be assumed for the whole race. Athletes showed a similar pacing pattern during RC and SC.

The higher variability at the end of the race is in line with recently observed higher variability at the end of 4km and 20km time trials in cycling [27, 28]. A reason for the increase in absolute variability could be the reduced uncertainty about the capability to perform the remaining part of the race, as the athlete approaches the endpoint [19, 29]. Furthermore, it has been suspected that prior experience is an important factor that an athlete can count on to generate a successful pacing profile at the beginning [19]. It can therefore be assumed that the high reproducibility of the first sections is the result of anticipation and prior experience [19]. In addition, a time delay in afferent feedback as described by Ulmer [31] might also be a possible explanation for the stable split times at the beginning and the increasing variability towards the end. As the endpoint of a race approaches, the occurrence of premature fatigue becomes less likely. Therefore, it seems reasonable that the perception of (possibly delayed) afferent signals gains importance and athletes rather adjust their velocity to afferent feedback from the periphery [21, 29]. The brain´s teleanticipatory centre algorithm would therefore set an overall pacing pattern at the beginning of the event, while feedback control would fine tune and continuously update the pacing to prevent catastrophic failure in peripheral physiological systems later during the race [25, 31].

All three distances showed a faster first section compared to all others. This is most likely due to the start dive acceleration. A beginning without a start dive might nullify this difference. Such results, however, would not be comparable to RC, where the first section was also similarly faster compared to all others. Additionally the start dive likely contributes to a consistent pace during the first lane and, thus, may be responsible for the relatively low CV during the first section of all three distances during SC (0.9–1.4%). In contrast cyclist showed highest CV at the beginning, likely due to the mechanical power needed to overcome rolling resistance at the start [27, 28]. Even though competition situations can induce anticipatory changes in cardiovascular and respiratory parameters of athletes [33], no difference in the pacing profile could be observed between RC and SC in this study. This leads to the assumption that SC can be used for investigating manipulations of pacing pattern during training. Furthermore, it can be speculated that patterns stored in the long-term memory during training can be carried into RC. Although pacing profiles were similar between SC and RC average race time was faster during the latter condition. In particular, performance difference was similar during all sections of the race. Corbett et al. [9] observed that this phenomenon occurs primarily via centrally mediated increased anaerobic energy yield in 14 cyclists during 2000m time trials (performance time about 185s). This finding points towards a physiological reserve [30].

In accordance with previous research, CV values for time to completion in simulated bouts were small (CV<1.5%) [18, 24, 27], and are comparable to those expected during actual performance in young athletes of national level [26]. Stewart and Hopkins [26] described a CV of about 1.5% for performance of junior and elite national swimmers between competitions. The reproducibility of total time in the present study seems thus acceptable for all three distances. This is in particular interesting for future studies on pacing. For instance, with a maximum CV of 1.5% a total sample size of 22 subjects is necessary to detect a worthwhile change in performance of 0.8% in swimmers between competitions (80% power) [5, 22, 32]. However, the transfer of the present results to the top level should be done with caution. The interpretation of the mostly higher CVs for the single sections is more complicated as no comparative data for swimming are available so far. As overall velocity is the mean of the section velocities, it is plausible that the relative error of most sections was higher as compared to total times.

Limitations

The subjects in the present study were junior swimmers. Prior experience has an influence on pacing pattern, especially on its stability [19]. Recently published data showed lower variability in overall performance for elite trained athletes compared to sub-elite ones [17, 26], hence, variability of pacing pattern might be smaller in elite swimmers. Therefore, it is possible that the reliability between test and retest has been underestimated compared to older or more experienced swimmers. Investigations with athletes of the highest international level remains an interesting topic for future research.

Foster suggested to measure split times every 5 to 10% of total performance time when analysing pacing profiles [13]. Whereas this is easily possible in a laboratory setting, it is much more complicated to measure split times in the pool independently of the given pool length. For the 800m the desired frequency was nearly reached. The chosen intervals in the present study are, however, relevant from a sports practical perspective.

The present study suffers from the low number of subjects for reproducibility analyses. This is especially a problem with regard to the uncertainty of the analyzed measures of absolute variability. Research in high performance sports inherently suffers from the low number of subjects of a sufficient performance level available at a single training center for such studies. Nevertheless, 16 subjects and in total 6 repeated trials were included in the present study. In addition, the confidence limits seem appropriately narrow. More research on the reliability of pacing profiles in competitive swimmers seems warranted, with particular regard to different strokes, distances and performance levels.

Conclusion

In conclusion, the present results show that high-level junior swimmers can perform self-paced 200, 400 and 800m bouts with good reproducibility [27, 28]. The assumption that pacing profiles are stable has been particularly confirmed for the first three quarters of the race. The last quarter showed greater absolute variability for each race distance. This leads to the assumption that anticipatory control and prior experience might be dominant during the race, whereas actual sensory feedback becomes more important during the final spurt. Described CVs are low enough to detect a worthwhile change in performance of 1% in high-level swimmers with a realistic amount of subjects (about 14). Furthermore, simulated trials seem to be an acceptable model to analyse pacing profiles in competitive swimming.

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Figure captions:

Fig. 1 Pacing pattern during simulated tests (solid lines) and retests (broken lines, data as means with SD, calculated from split times relative to the mean velocity) and log-transformed coefficients of variation (CV) with 90% confidence intervals (bars with whiskers) for all three distances.

Fig. 2 Pacing pattern during simulated (solid lines) and real competition (broken lines, data as means with SD, calculated from split times relative to the mean velocity) and log-transformed coefficients of variation (CV) with 90% confidence intervals (bars with whiskers) for all three distances.

Fig. 3 Bland-Altman plots showing the within-subject variation in total time for test-retest comparison (left hand side) as well as for the comparison between real (RC) and simulated competition (SC, right hand side) for all three distances (dotted lines showing the 95% limits of agreement, solid lines the mean bias between trials)

Table 1 Average results during test, retests and real competitions for all subjects. Data as mean±standard deviation.

Test	**800m test**	**800m retest**	**800m competition**	**400m test**	**400m retest**	**400m competition**	**200m test**	**200m retest**	**200m competition**
N	m 9; f 7	m 9; f 7	m 8; f 4	m 7; f 7	m 7; f 7	m 7; f 6	m 6; f 5	m 6; f 5	m 6; f 5
Time male subjects [min]	9:07,4 ±0:22,2	9:10,0 ±0:22,4	9:03,6 ±0:31,1	4:23,0 ±0:11,1	4:24,5 ±0:09,5	4:20,8 ±0:16,6	2:03,9 ±0:05,7	2:05,3 ±0:05,3	2:00,2 ±0:06,5
Time female subjects [min]	9:57,1 ±0:16,5	10:03,3 ±0:21,7	9:32,8 ±0:14,7	4:50,4 ±0:09,3	4:52,0 ±0:10,1	4:41,5 ±0:11,0	2:18,5 ±0:05,8	2:16,5 ±0:04,0	2:14;0 ±0:06,9
bLa_{end} [min^{-1}]	7.9±2.5	8.3±3.0		9.6±2.2	10.2±2.6		11.1±2.3	10.8±3.5	
HR_{end} [bpm]	176±23	186±9		180±6	181±7		179±9	181±10	

Table 2 Standard error of measurement (SEM) and 90% confidents limits (CI) for each single section (S) as well as total time (TT) in test, retest (SC) and competition (RC) of all three bouts. For 200m real competition only data for both 100m sections was available.

		TE (s) (90% CI)								
		S 1	S 2	S 3	S 4	S 5	S 6	S 7	S 8	TT
800m	test/retest	0.6 (0.5–1.2)	0.8 (0.6–1.2)	1.0 (0.8–1.5)	1.2 (0.9 – 1.8)	1.2 (0.9–1.7)	1.3 (1.0–1.9)	1.8 (1.4–2.6)	2.1 (1.6–3.0)	8.7 (6.7–12.5)
	SC/RC	1.8 (1.3–2.8)	1.4 (1.0–2.2	1.2 (0.9–1.9)	1.2 (0.9 – 1.9)	1.6 (1.2–2.5)	1.6 (1.2–2.5)	2.0 (1.5–3.1)	2.2 (1.5–3.1)	10.8 (8.1–16.8)
400m	test/retest	0.7 (0.6-1.1)	0.6 (0.4-0.9)	1.2 (0.9-1.8)	1.7 (1.3-2.5)					2.4 (1.8-3.6)
	SC/RC	1.5 (1.1-2.2)	1.5 (1.1-2.2)	1.3 (1.0-1.9)	1.8 (1.4-2.7)					4.3 (3.3-6.4)
200m	test/retest	0.4 (0.3-0.6)	0.4 (0.3-0.6)	0.6 (0.4-0.9)	0.8 (0.6-1.2)					1.2 (0.9-2.0)
	SC/RC	1.4 (1.1-2.2)		2.1 (1.6-3.2)						3.4 (2.5-5.2)

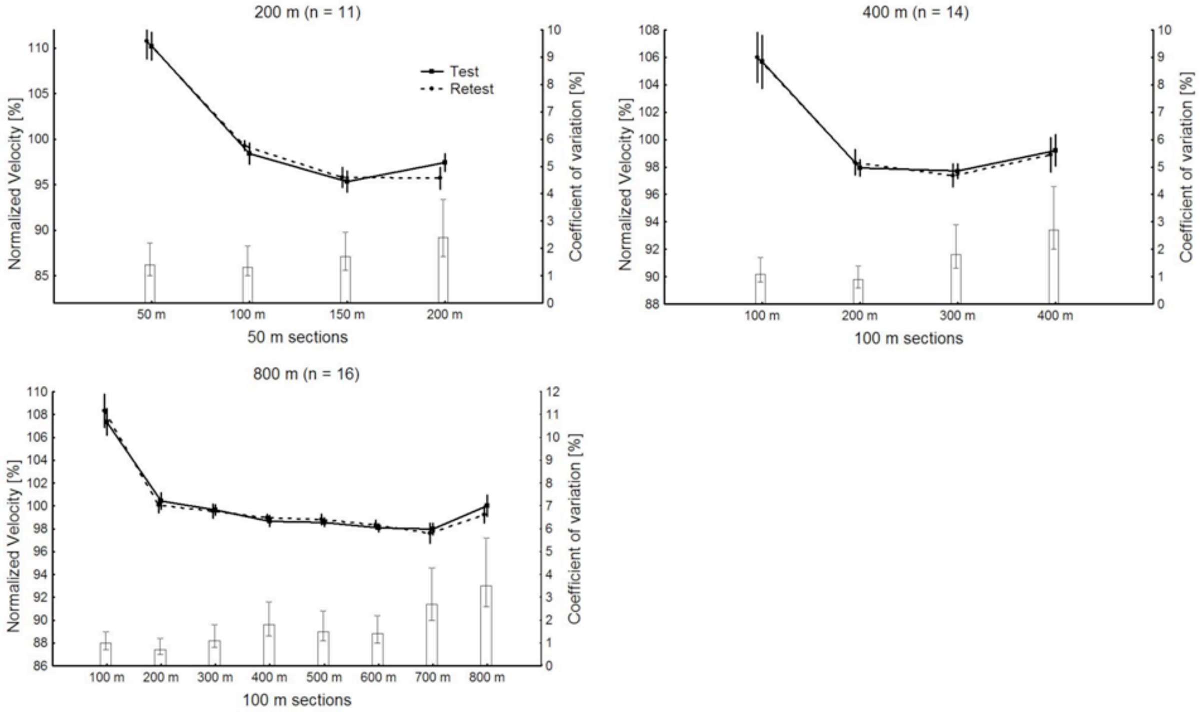


Fig. 1 Pacing pattern during simulated tests (solid lines) and retests (broken lines, data as means with SD, calculated from split times relative to the mean velocity) and log-transformed coefficients of variation (CV) with 90% confidence intervals (bars with whiskers) for all three distances.

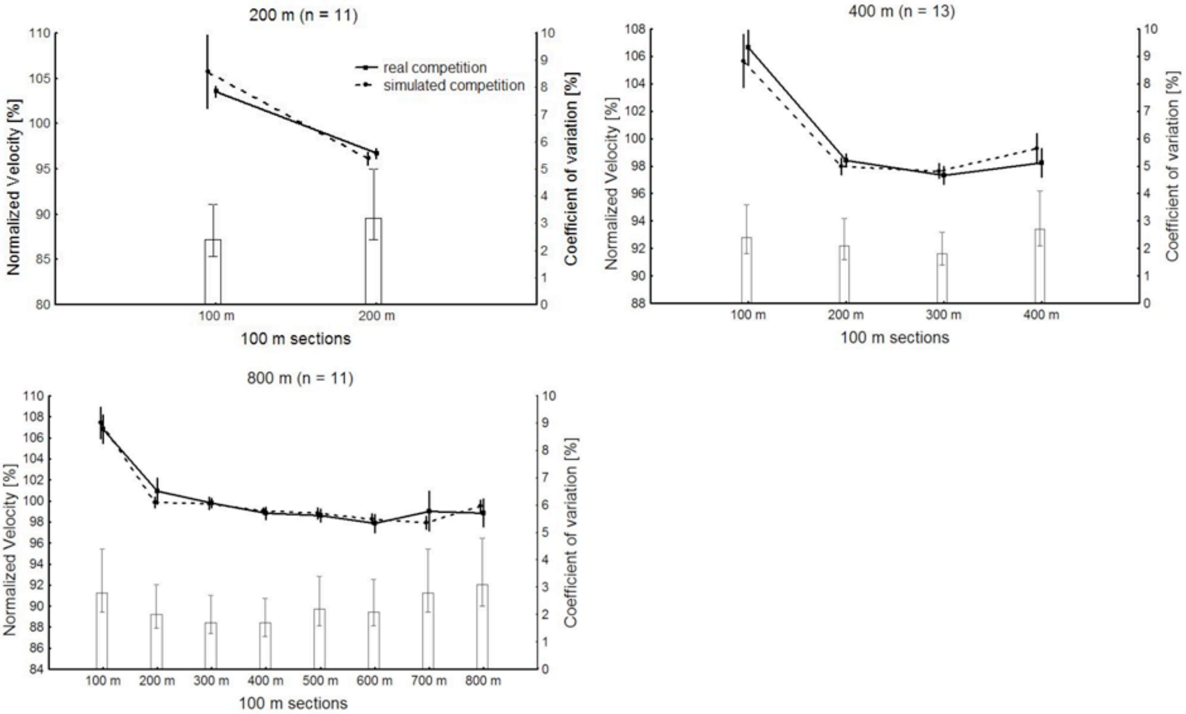
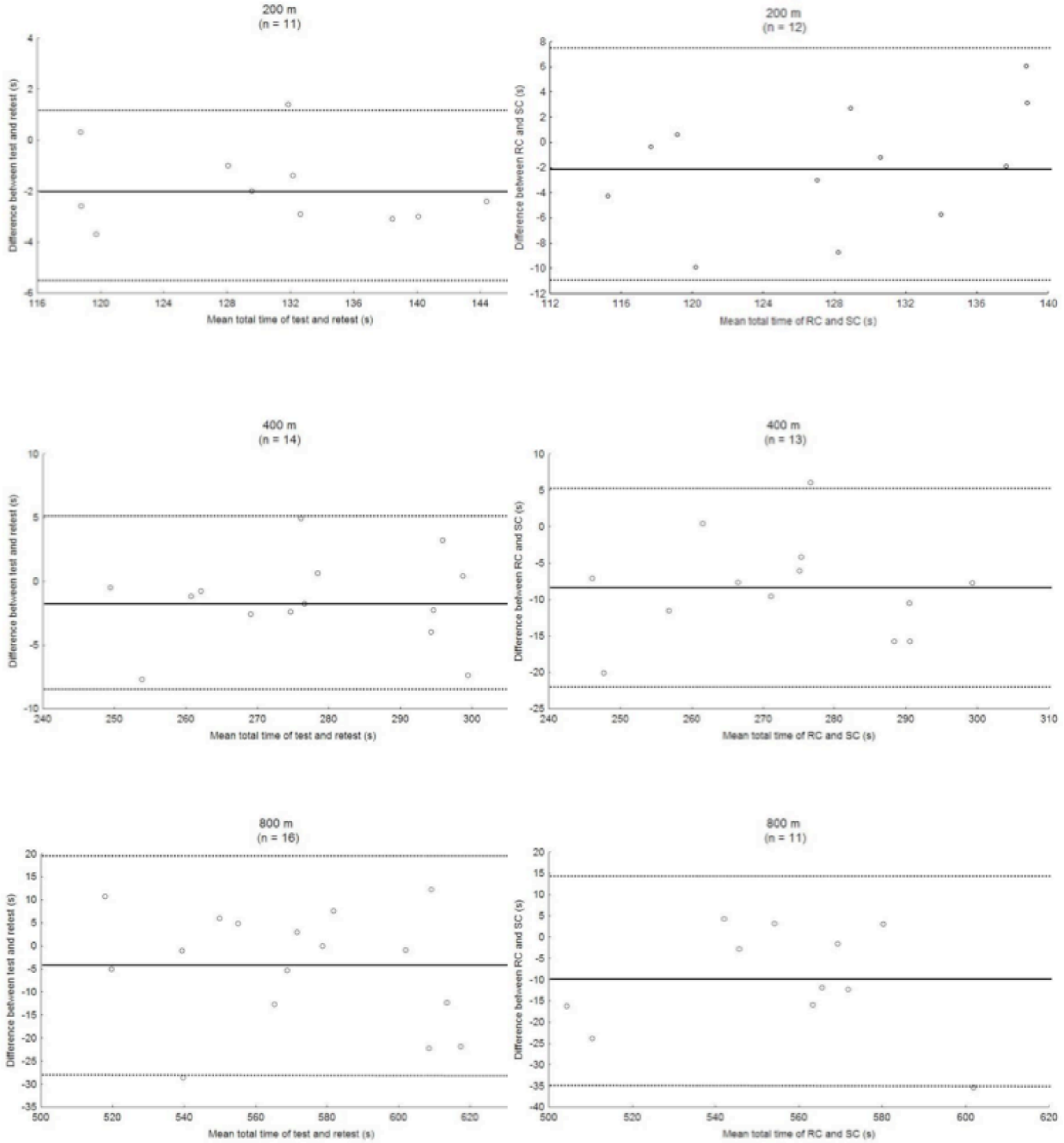


Fig. 2 Pacing pattern during simulated (solid lines) and real competition (broken lines, data as means with SD, calculated from split times relative to the mean velocity) and log-transformed coefficients of variation (CV) with 90% confidence intervals (bars with whiskers) for all three distances.



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Section: Original Investigation

Article Title: Reproducibility of Competition Pacing Profiles in Elite Swimmers

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Abstract

Purpose: The aim of this study was to analyze the reproducibility of pacing in elite swimmers during competitions and to compare heats and finals within one event. **Methods:** Finals and heats of 158 male swimmers (age: 22.8±2.9y) from 29 nations were analysed in two competitions (downloaded from swimrankings.net). 134 were listed in the World´s Top 50 in 2010, the remaining 24 were finalists of the Pan Pacific Games or European Championships The level of both competitions for the analysis had to be at least national Championships. (7.7±5.4 weeks apart). Standard error of measurement expressed as percent of the subject´s mean score (CV) with 90% confidence limits (Cl) for each 50m split-time and for total times were calculated. Additionally mixed general modelling was used to determine standard deviations (SD) between and within swimmers. **Results**: CV for total time in finals ranged between 0.8 and 1.3% (Cl: 0.6-2.2%). Regarding split times, 200m freestyle showed a consistent pacing over all split times (CV: 0.9-1.6%). During butterfly, backstroke and 400 m freestyle CVs were low in the first 3 and 7 sections, respectively (CV: 0.9-1.7%), with greater variability in the last one (1.9-2.2%). In breaststroke values were higher in all sections (CV: 1.2-2.3%). Within-subject SDs for changes between laps were between 0.9 and 2.6% in all finals Split time variability for finals and heats ranged between 0.9 and 2.5% (Cl:0.3-4.9%). **Conclusion**: Pacing profiles are consistent between different competitions. Variability of pacing seems to be a result of the within-subject variation rather than a result of different competitions

Key words: consistency, swimming, sports performance, pacing template

Introduction

In most endurance events, the goal of each athlete is it to cover a given distance in the shortest possible time. Hence it is essential to use the available energetic resources efficiently to balance speed in a way that will allow completion of the activity to the best of each athlete's capacity.[1-3] Accordingly, it is widely accepted that the adoption of a suitable pacing pattern is an important determinant of success[4-6] and it is inextricably linked to the individual's regulation of the rate of fatigue development over the duration of exercise.[4]

Mostly described profiles in middle distance events are fast-start even,[4] fast-slow and slow-fast pattern.[5,7] In the current scientific literature it is speculated that pacing is a combination of anticipatory forecasting, feedback integration and previous experience.[2,4, 5, 7-9] Furthermore, most authors suspect that after a particular competition the pacing pattern is restored in the long-term memory and used as a schema for similar bouts in the near future.[2,10] In support of this concept published data suggest either a conscious or subconscious "teleoanticipation" in which athletes optimize performance while minimizing the likelihood of catastrophic failure.[3,11] It is assumed that this template cannot be willingly changed from race to race.[12-14]

To analyze the influence of the described mechanisms on pacing and to examine if the template is programmed into the motor cortex[13] it is desirable to know if a chosen pattern is consistent from race to race. However, there is only little data available about the day-to-day variation of pacing patterns in simulated or real competitions.[10,12,15] Stone et al.[10] found a stable pattern in 4 km cycling time trials with a coefficient of variation (CV) of about 2% in the middle, with higher variability at the beginning and the end of the race. Similar results were observed by Thomas et al.[12] during 20 km time trials. However, both studies were conducted in the laboratory, therefore it might be speculated that environmental conditions (e. g. wind, terrain) can lead to different results in real competitions.

Since there are higher resistive forces (e. g. drag) in swimming a greater significance of pacing on performance outcome has been assumed.[4] But most data on reliability of performance in swimming competitions focus on overall time[16-18]. To the authors knowledge, only one study analyzed the reliability of pacing pattern in swimming events yet.[15] A stable pattern was observed at the beginning of 200, 400 and 800 m front crawl races (CV < 2%) with an increasing variability in the last quarter of each bout (CV up to 2.9%).[15] In addition, little difference could be observed in pacing between real and simulated competitions, hence the authors concluded that simulated swimming competitions are likely to be a useful tool for interventions on pacing with junior swimmers.[15] However, taking into consideration that prior experience has a major influence on pacing patterns[2], it is not sure if these results can be transferred to more experienced or yet world-class swimmers. Some authors also suspect that tactical influences and different opponents might lead to changes in the pacing pattern between different competitive events.[4] Up to now there is no data available on the reproducibility of pacing patterns during competitions in elite swimmers, neither between different events nor within one competition (e. g. heat vs. final race).

Therefore, the aim of the study was to analyse the reliability of pacing between competitions in world-class swimmers, and to examine possible differences between heats and finals within the same competition. Based on published results[15] it was hypothesized that the pacing pattern of elite swimmers is consistent between different competitions and that swimmers do not change their racing profile relevantly due to tactical considerations.

Methodology

Subjects

All procedures are in accordance with the declaration of Helsinki and were approved by the local ethics committee (Ärztekammer des Saarlandes, Saarbrücken, Germany).

Informed consent was not considered necessary to be obtained from swimmers for use of this publicly accessible information.

The World´s Top 50 ranking of the year 2010 was used as basis for the analysis of each stroke (n = 250). 116 swimmers were excluded since split times were not available for two competitions close enough to each other. Furthermore, swimmers who were not listed in the ranking but qualifiers for the A- or B-final in the Pan Pacific Games and/or European Championships 2010 were also included (n = 24). Therefore, a total of 362 races (182 finals, 180 heats) of 158 different elite male swimmers (age: 22.8 ± 2.9 y) from 29 nations in 200 m freestyle (n = 44), butterfly (n = 35), backstroke (n = 35) and breaststroke (n = 35) as well as 400 m freestyle (n = 33) were analysed retrospectively. 24 swimmers competed in more than one stroke and/or distance in the chosen competitions and are included in more than one analysis (n = 16 in 200 and 400 m freestyle, n = 4 in 200 m freestyle and butterfly, n = 3 in 200 m freestyle and backstroke, n = 1 in 200 m freestyle, butterfly and backstroke). Official split times in heats were not available for two swimmers, so 156 were taken into consideration for the comparison of heat and final race. Individual medley was left out due to the stroke dependent differences in velocity within one race.

Events

Overall 22 national and international events in the year 2010 (January until December) were examined in the current analysis. Data were obtained using the website www.swimrankings.net, which is based on information from the European Swimming Federation (LEN) database and the results from the Belgian, Canadian, Dutch, Polish, Portuguese and Swiss Federations. All events were swum in long-course (50 m) pools. Since a crucial change in overall performance was expected in the year of the Olympic Games as well as the year before and after, events from the year 2010 were chosen for the current analysis. In the middle of one Olympic cycle, a more stable performance level over the season was anticipated. High tech swim suits were not allowed anymore hence all swimmers were only allowed to wear trunks up to the knee (FINA Swimming rules, 2010). Competitions were on average 7.7 ± 5.4 weeks apart with a maximum of 29 weeks. Total and all 50 m split times were downloaded from the official swimming websites www.swimrankings.net. In all events automatic officiating equipment was used under the supervision of appointed officials to determine total times as well as all 50 m split times (according to the FINA swimming rules).

Statistical analysis

Data are presented as means and standard deviations (SD). For finals the average race velocity ($m*s^{-1}$) was calculated, so that the velocity in each split could be expressed in relation to overall race velocity (normalised mean velocity). This approach of expressing pacing as the difference between current and overall mean velocity is well accepted.[5] The comparison of heat and final race was analysed with absolute values (in s), to illustrate the difference in absolute split times between the races more clearly. The later competition of each subject was used for the analysis of heat and final race. Standard error of measurement (SEM) expressed as a percent of the subjects´ mean score (coefficient of variation, CV) with 90% confidence limits (Cl) were calculated for all 50 m split times and total times using a published spreadsheet[19] in Microsoft Excel (2007). All performance times were log-transformed for the analyses, then back-transformed to obtain changes in means and variation as percentages, according to existing methods.[19, 20] Statistical analysis was conducted using Statistica (Version 6, Ed. ´02, StatSoft Inc., Tulsa, OK, USA). A repeated measures ANOVA (factor 1: competition; factor 2: section of the race) was used to test for global effects between competition one and competition two as well as between heat and finals (later competitions were used for the analysis of the pacing pattern in heats and finals). In case of a significant global effect post-hoc analysis was carried out using the Scheffé-Test.

Furthermore, reproducibility of pacing pattern was analysed using the change score between the laps in percent. Therefore, the difference between every split time was calculated as percent of the preceding 50 m lap (e.g. Δ lap 1-2 for the difference between split time 1 and 2 in a race). Reliability of changes between single laps was analyzed with mixed general models using Stata (StataCorp, Release 12. Statistical Software. College Station, TX: StataCorp LPTexas, USA), as recently published.[21] Therefore, competition was included as fixed effect and the random effects were swimmers´s identity (between subject variability) and the residual (within-subject variability).

Results

Overall Results

Total times in competition one and competition two in both heats and finals are shown in table 1 . Total time of finals was significantly faster in all 200 m strokes during competition two ($p < 0.001$). Total times in 400 m freestyle showed no difference between both competitions ($p = 0.97$). In competition one finals were on average 2.3 s (± 4.3 s) faster than the corresponding heats ($p<0.001$). In competition two the difference between heats and finals was 1.1 s (± 1.9 s, $p<0.001$). Average performance improvement from heat to final was 1.2% (Cl: 0.6 – 2.2%) including both competitions.

Pacing pattern in second finals and heats

The normalized profiles for finals in both competitions are shown in figure 1. With regard to pacing pattern swimmers adopted a fast-start even profile in 200 m freestyle, butterfly and backstroke with a significantly faster first section in all bouts ($p < 0.001$ to all others), as well as a faster second split time compared to split three and four in freestyle and backstroke ($p < 0.001$). Breaststroke showed a fast-slow profile with significant differences between each 50 m split time ($p < 0.001$). During 400 m freestyle swimmers adopted a parabolic shaped pattern, racing the first section faster than all others ($p < 0.001$), and showing a higher split velocity in the last section compared to all others ($p < 0.001$). Figure 2 illustrates the pacing profiles (in s) in heats and finals for all analysed strokes and bouts. Swimmers paced their heat similar to finals in all strokes and races (interaction: all $p > 0.06$). However, average 50 m split times were significantly faster in finals compared to heats ($p < 0.02$).

Reproducibility of pacing pattern in finals as well as heat vs. final

Normalized pacing pattern was not significantly different between competition one and two ($p > 0.18$, figure 1) in all strokes and distances. CV (%) and 90% Cl for each section, as well as for total time between both competitions are shown in table 1. Table 2 shows the mean change in percent between each lap in all strokes for final races, as well as the standard deviation (SD) of the change estimated by mixed modelling. Mean lap change ranged between -13.3% (Δ lap 1-2 in 200 m butterfly) and -0.2 % (Δ lap 5-6 in 400 m freestyle). Within-swimmer SD in lap change ranged between 0.9 and 2.6% (range in 90% Cl: 0.8 – 3.2%), between-swimmer SD from < 0.001 to 1.8% (Cl: < 0.001 and 5.3%).

CV for intra-individual differences in split times between heats and finals were small for all 200 m races (< 2.2.%; Cl: 0.6 – 3.2%). In 400 m freestyle values increased in the course of the race up to 2.9% in the last section (Cl: 2.2 – 4.5%). Mean difference in total time ranged from 1.0 s (Cl: 0.7 – 1.3 s) in 200 m freestyle (CV: 0.9%; Cl: 0.7 – 1.2%) to 2.7 s (Cl: 1.5 – 4.0 s) in 400 m freestyle (CV: 1.3%; Cl: 1.0 – 2.0%). Table 3 shows the results of mixed modelling for the comparison of heat and final race in competition two. Mean lap change lies between -13.4% (Δ lap 1-2 in 200 m butterfly) and -0.08% (Δ lap 5-6 in 400 m freestyle). Within-swimmer SD in lap change showed values between 0.9 and 3.0% (range in 90% Cl: 0.8 – 3.2%), between-swimmer SD from < 0.001 to 2.0% (Cl: <0.001 and 2.5%).

Discussion

Based on our results pacing seems fairly consistent between competitions in elite swimmers. The stable profile between different swimming events is in accordance with recently published findings in simulated competitions of competitive junior swimmers.[15] Even though the younger swimmers showed slightly higher variability in the last quarter of the simulated competitions (CV up to 6%) this leads to the assumption that results of future studies on pacing conducted with experienced junior athletes are relevant for/transferrable to elite swimmers as well. Contrary to existing theories[4,22] world-class swimmers do not seem to modify their pacing relevantly due to varying race tactics or different types of competitions. The stability of pacing patterns might, however, be a typical "phenomenon" for swimming events. In swimming competitions swimmers are more "isolated" from their opponents compared to other endurance sports like running or cycling in that no opponent can cross the swimmers´ lane. For the swimmer it seems to represent the best solution to rely on his own individual racing template based on prior experience.[2] In all strokes the random within-subject standard deviation of the change scores between the laps was higher than the random between-subject deviation. Therefore, it is most likely that the variation in the pacing profile comes from the variability of the swimmer himself rather than from differences between competitors.

Breaststroke showed higher variability over the whole race. This could be due to the higher velocity fluctuations within one swimming cycle leading to significantly higher energy expenditure.[23] Therefore it can be assumed that the chosen pattern needs more "adjusting" during the race, depending on carbohydrate status and/or the influence of earlier events on the specific day. Regarding the chosen pacing template swimmers showed a fast-start even and fast-slow pacing during the 200 m bouts as well as a parabolic shaped pattern during 400 m. These profiles are in accordance with recently published findings of elite swimmers competing at similar events (British and Australian championship, European championship and Commonwealth Games).[4]

The within-subject variability of overall performance represents the expected variation in elite swimmer's performance between competitions and is in accordance with the scientific literature for swimming competitions.[16-18] The value of 1% for the mean CV of performance time between competitions in this cohort of world-class swimmers is somewhat smaller than the 1.5% reported previously for simulated freestyle competitions in junior swimmers.[15] The greater consistency of the international swimmers may be due to a greater competitive experience. However, it is noteworthy that all finals in the second competition were significantly faster compared to the first ones in the 200 m bouts. This could be an effect of the difference of almost 8 weeks between both competitions and the fact that in most swimmers the second analyzed competitions were the Pan Pacific Games or the European Championship ,hence the main event of the season. In this regard, as described by Pyne et al.,[17] a performance improvement of 1% can be possible leading up to the main event of a season. Otherwise, it could be suspected that the difference between competitions is an effect produced by the homogeneity of the analysed swimmers (all male swimmers, time difference between the first and the last in the Top 50 about 5 s). However, difference between competition performances was 0.9% and therefore slightly above the smallest worthwhile change described in several studies on competition reliability (about 0.3%).[16,17,24] Furthermore, Mujika et al.[24] described a difference in performance time between the gold medallist and the 4th place of 1.6% at the 2000 Olympic Games, so the difference in the current study might be significant yet not inevitably relevant.

The variation in overall performance time between heat and final within one event is also similar to previously published studies. Pyne at al.[17] described a CV of 0.7 to 1% between heats and semi-finals for US and Australian Olympic swimmers. Average performance improvement from heat to final in the current study was 1.2%. However, regarding the pacing pattern in heats and finals swimmers showed small variability at the beginning, with a slight increase towards the end. Therefore, it is reasonable to assume that elite swimmers mostly choose “their” pacing template independent of the race type, yet with a slower average velocity. In spite of that, the variability increased in the last section of 200 m backstroke and breaststroke as well as 400 m -freestyle. This might be explained by the issue of performance progression within and between races, which is fundamental to competitive swimming.[17] Progressions are generally required to ensure that a swimmer qualifies for the semi-finals and then the finals, and that the peak performance is produced in the final, where medals are decided.[17] Depending on the competitors in a heat, better swimmers might hold back in the end of the heat to save energy stores for later competitions on the day.[17] Even so, some swimmers were slower in the final race compared to the heat (n = 27 equal to 15% of all swimmers). With regard to pacing pattern these subjects started their final race on average 9.2% above their individual mean velocity, whereas in the corresponding heat the same swimmers began with 8.9% above their average velocity. In contrast, the other 153 subjects paced the starting 50 m section slightly slower than the corresponding heat (8.0% above the individual mean velocity) resulting in a faster total time compared to their heats. During middle distance events, athletes distribute their energetic resources over the duration of the event in a manner that preserves the ability to provide for anaerobic output until the closing stages of the event.[1,3] In swimming any fluctuation in velocity could create higher relative energy cost because of the higher resistive forces than in other sports.[25,26] Therefore, it is speculated that these swimmers used a larger amount of their anaerobic capacity at the beginning of the race, which might have caused a meaningful slow down at the end.[27,28] However, the reason for this faster start remains unknown.

Given that this investigation was purely observational and retrospective, the influence of factors such as motivation, shaving, different swimming suits or diet could not be controlled for. Thus internal validity of this study might be lower than in typical experiments. However, results are similar to studies carried out either in the laboratory[10,12] or under standardized conditions.[15] Regarding high tech swim suits their use was not allowed anymore with the beginning of 2010 (according to the FINA swimming rules). Furthermore, Mauger et al.[4] recently described that pacing pattern is independent of swim suit design. Since analysed data were taken from real competitions in high-level swimmers a high external validity is ensured and results are applicable for the highest performance level.

Difference between analysed competitions was on average 7.7 weeks with a maximum of 29 weeks. With regard to performance enhancement due to training, test and retest should be as close as possible for reliability studies. However, CV of overall performance times is in accordance with the scientific literature on competition variability[16,17] as well as with studies conducted in the laboratory.[29,30] It might as well be speculated that the importance of the competition has a larger influence on competition reproducibility in elite swimmers than the time difference between events. Therefore, only major competitions during one year were taken into consideration for the current investigation (e.g. continental and national championships). Furthermore, as described earlier, it is suspected that overall performance time is rather influenced by the seven weeks between both competitions, not the pacing pattern.

Conclusion and Practical Application

In conclusion elite swimmers seem to have a stable pacing pattern between different competitions and within one event. Occurring variations in the pattern seem to be related to the swimmer himself rather than to different competitors or competitions. In this regard prior experience seems to have a large influence, since variability was smaller in elite swimmers compared to younger ones.[15] However, it is still not sure if the chosen pacing is optimal for each individual swimmer. Based on the current results it can be suspected, that a change in the pacing template needs training and competition experience to restore the pattern in the long-term memory and change the program in the motor cortex.[2,13] In terms of future research this paper can only speculate about possible underlining physiological mechanisms of the chosen pacing pattern. This is especially interesting when performance was worse in a final race compared to the corresponding heat.

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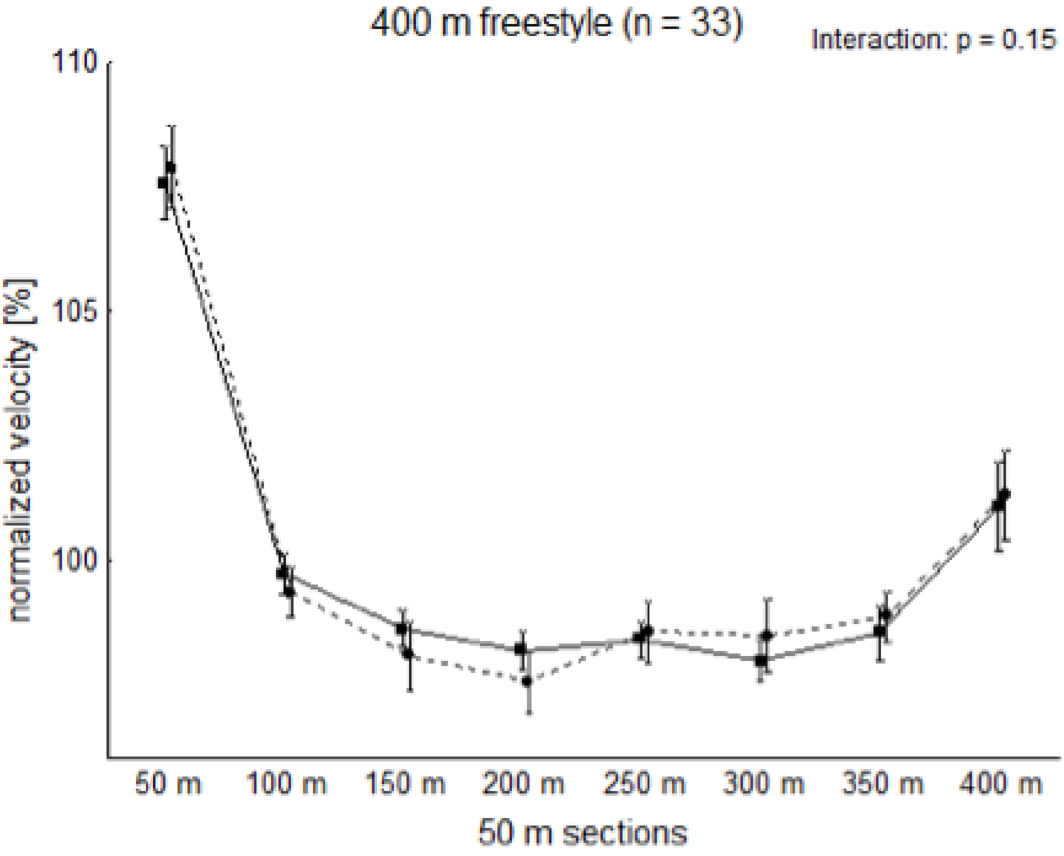

Figure 1. Normalized pacing pattern during competition one (solid lines) and two (dashed lines; data as means with SD, calculated from split times relative to the mean velocity) and log-transformed coefficients of variation (CV) with 90% confidence intervals (bars with whiskers) for all 200 m races as well as 400 m front crawl.

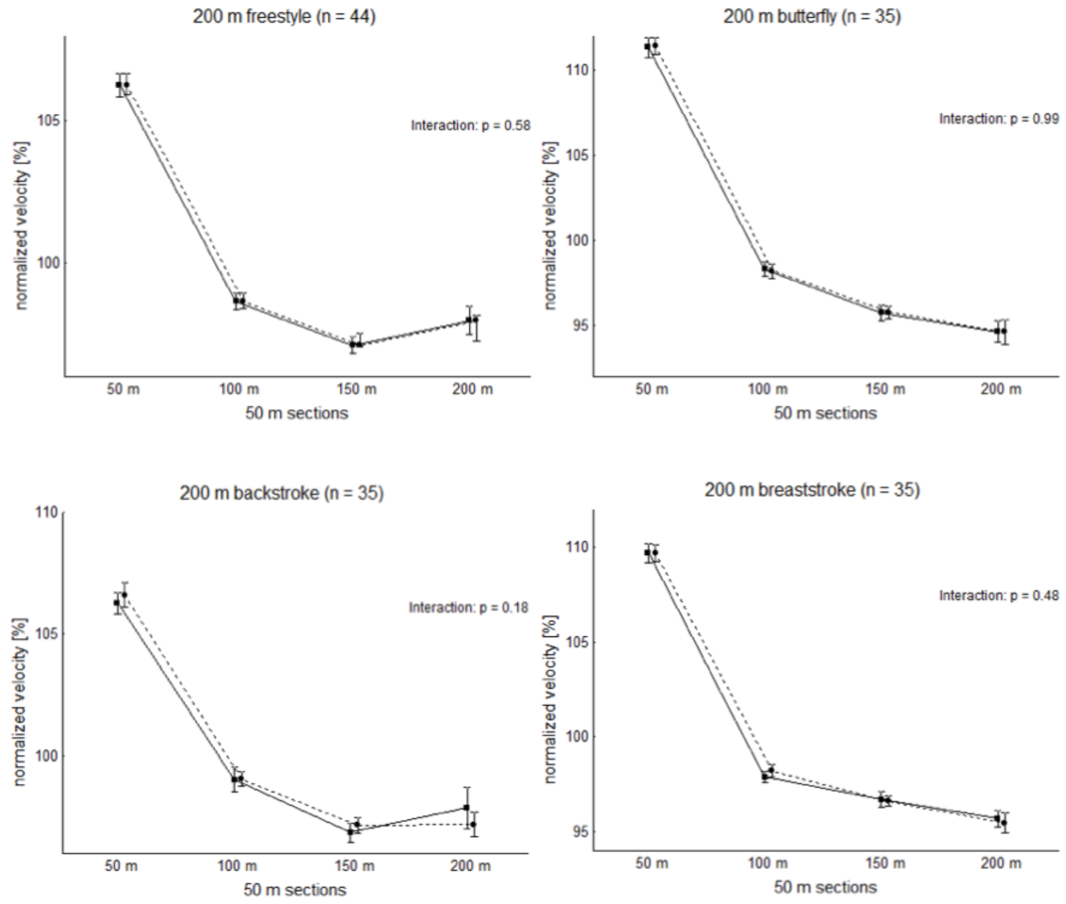

Figure 2. Pacing pattern during final (solid lines) and heat (dashed lines) of competition two (data as means with SD) and log-transformed coefficients of variation (CV) with 90% confidence intervals (bars with whiskers) for all 200 m races described in absolute 50 m split times.

Table 1 – Overall results of heat and final races in competition 1 and 2 in all strokes and distances (Data as mean and ± standard deviation), as well as standard error of measurement expressed as a percent of the subjects mean score (Coefficient of variation, CV) of all split times.

		200 m Freestyle	**200 m Butterfly**	**200 m Backstroke**	**200 m Breaststroke**	**400 m Crawl**
Competition 1	Heat 1	110.7 (± 2.0)	121.8 (± 3.7)	122.8 (± 2.8)	136.1 (± 3.3)	235.6 (± 4.5)
	Final 1	109.3 (± 1.8)	119.3 (± 3.8)	120.5 (± 2.2)	133.9 (± 2.5)	231.8 (± 3.7)
Competition 2	Heat 2	109.6 (± 2.0)	119.7 (± 2.8)	120.6 (± 2.2)	134.2 (± 2.5)	234.3 (± 7.1)
	Final 2	108.8 (± 1.8)	118.2 (± 3.4)	119.4 (± 2.4)	132.9 (± 2.0)	232.4 (± 5.6)
CV (%) split times final 1 and final 2	50 m	1.2 (0.9 – 1.7)	1.7 (1.3 – 2.2)	0.9 (0.7 – 1.3)	1.8 (1.3 – 2.6)	1.2 (0.9 – 1.8)
	100 m	1.6 (1.2 – 2.3)	1.5 (1.1 – 2.2)	1.1 (0.9 – 1.6)	1.2 (0.9 – 1.8)	1.3 (1.0 – 1.9)
	150 m	0.9 0.7 – 1.4)	1.6 (1.2 - 2.3)	1.6 (1.2 – 2.3)	1.4 (1.1 – 2.1)	1.0 (0.8 – 1.6)
	200 m	1.0 (0.8 – 1.6)	1.9 (1.5 – 2.7)	1.9 (1.4 – 2.7)	2.3 (1.7 – 3.4)	1.2 (0.9 – 1.8)
	250 m					1.4 (1.1 – 2.1)
	300 m					1.4 (1.0 – 2.1)
	350 m					1.7 (1.3 – 2.7)
	400 m					2.2 (1.7 – 3.4)
	Total time	0.8 (0.6 – 1.2)	0.8 (0.6 – 1.2)	0.9 (0.7 – 1.3)	1.3 (1.0 – 1.9)	1.3 (1.0 – 2.2)
CV (%) split times heat 2 and final 2	50 m	1.1 (0.8 – 1.6)	0.9 (0.7 – 1.4)	1.0 (0.7 – 1.4)	1.1 (0.8 – 1.8)	1.3 (1.0 – 2.0)
	100 m	1.3 (1.0 – 2.0)	2.0 (1.5 – 3.1)	1.2 (0.9 – 1.8)	0.9 (0.6 – 1.4)	1.5 (1.1 – 2.3)
	150 m	1.6 (1.2 – 2.3)	1.6 (1.2 – 2.5)	1.3 (1.0 – 1.9)	1.4 (1.0 – 2.0)	1.6 (1.2 – 2.5)
	200 m	0.9 (0.7 – 1.3)	1.6 (1.2 – 2.4)	2.2 (1.6 – 3.2)	1.7 (1.3 – 2.5)	1.7 (1.3 – 2.7)
	250 m					2.0 (1.5 – 3.1)
	300 m					2.5 (1.9 – 3.8)
	350 m					1.9 (1.4 – 2.9)
	400 m					2.9 (2.2 – 4.5)
	Total Time	0.9 (0.7 – 1.2)	2.5 (1.9 – 3.8)	0.8 (0.6 – 1.3)	0.8 (0.6 – 1.2)	1.3 (1.0 – 2.0)

Table 2 – Mean split time change between the single laps (%), as well as within-subject and between-subject standard deviation (SD) of the change both final races in all strokes and distances (All data ± 90% Confidence limits, Cl).

Stroke	**Mean change between laps (%, ± 90% Cl)**	**SD (%, ± 90% Cl)**	
		Between competition within subjects	**Between subjects**
200 m Freesytle (n = 44)			
Δ lap 1-2	-7.7 (± 0.3)	1.1 (± 0.2)	1.0 (± 0.3)
Δ lap 2-3	1.5 (± 0.2)	1.2 (± 0.2)	0.5 (± 0.4)
Δ lap 3-4	-0.6 (± 0.3)	1.5 (± 0.3)	1.2 (± 0.5)
200 m Butterfly (n = 35)			
Δ lap 1-2	-13.3 (± 0.4)	1.9 (± 0.4)	1.0 (± 0.7)
Δ lap 2-3	2.6 (± 0.4)	2.0 (± 0.3)	< 0.001*
Δ lap 3-4	1.2 (± 0.5)	2.6 (± 0.5)	0.4 (< 0.001)*
200 m Backstroke (n = 35)			
Δ lap 1-2	-7.5 (± 0.3)	1.2 (± 0.2)	1.0 (± 0.4)
Δ lap 2-3	2.1 (± 0.3)	1.4 (± 0.3)	0.6 (± 0.6)
Δ lap 3-4	-0.5 (± 0.5)	2.4 (± 0.5)	0.7 (0± 2.6)
200 m Breaststroke (n = 35)			
Δ lap 1-2	-11.8 (± 0.3)	1.5 (± 0.3)	0.6 (± 0.8)
Δ lap 2-3	1.5 (± 0.3)	1.3 (± 0.2)	1.1. (± 0.4)
Δ lap 3-4	1.1 (± 0.4)	1.7 (± 0.3)	0.7 (± 0.9)
400 m Crawl (n = 33)			
Δ lap 1-2	-8.2 (± 0.4)	1.1 (± 0.2)	1.8 (± 0.4)
Δ lap 2-3	-1.3 (± 0.2)	1.0 (± 0.2)	0.6 (± 0.4)
Δ lap 3-4	-0.4 (± 0.2)	0.9 (± 0.3)	0.5 (± 0.3)
Δ lap 4-5	0.6 (± 0.4)	2.1 (± 0.3)	< 0.001*
Δ lap 5-6	-0.2 (± 0.2)	1.0 (± 0.2)	0.5 (± 0.4)
Δ lap 6-7	0.6 (± 0.4)	1.7 (± 0.3)	1.0 (± 0.4)
Δ lap 7-8	2.5 (± 0.5)	1.8 (± 0.4)	1.4 (± 0.6)

Table 3 – Mean split time change between the laps (%), as well as within-subject and between-subject standard deviation (SD) of the change for final and heat races in all strokes and distances in the second competition (All data ± 90% Confidence limits, Cl).

Stroke	**Mean change between laps (%, ± 90% Cl)**	**SD (%, ± 90% Cl)**	
		Between competition within subjects	**Between subjects**
200 m Freestyle (n = 44)			
Δ lap 1-2	-7.9 (± 0.3)	1.3 (± 0.2)	0.9 (± 0.4)
Δ lap 2-3	-1.7 (± 0.2)	1.3 (± 0.2)	< 0.001*
Δ lap 3-4	0.8 (± 0.4)	1.4 (± 0.3)	1.3 (± 0.4)
200 m Butterfly (n = 33)			
Δ lap 1-2	-13.4 (± 0.4)	1.4 (± 0.3)	1.2 (± 0.5)
Δ lap 2-3	-2.7 (± 0.4)	1.6 (± 0.3)	1.0 (± 0.5)
Δ lap 3-4	-0.9 (± 0.5)	1.9 (± 0.4)	1.7 (± 0.6)
200 m Backstroke (n = 35)			
Δ lap 1-2	-7.6 (± 0.3)	1.1 (± 0.2)	1.1 (± 0.3)
Δ lap 2-3	-2.1 (± 0.3)	1.2 (± 0.2)	0.8 (± 0.4)
Δ lap 3-4	-0.2 (± 0.5)	1.9 (± 0.4)	1.2 (± 0.6)
200 m Breaststroke (n = 35)			
Δ lap 1-2	-11.7 (± 0.3)	1.3 (± 0.3)	1.0 (± 0.4)
Δ lap 2-3	-1.8 (± 0.3)	1.3 (± 0.3)	0.6 (± 0.5)
Δ lap 3-4	-1.3 (± 0.4)	2.0 (± 0.4)	0.8 (± 1.0)
400 m Crawl (n = 33)			
Δ lap 1-2	-8.5 (± 0.9)	1.0 (± 0.2)	2.0 (± 0.5)
Δ lap 2-3	-1.5 (± 0.7)	1.0 (± 0.2)	1.3 (± 0.4)
Δ lap 3-4	-0.4 (± 0.4)	0.9 (± 0.4)	0.5 (± 0.3)
Δ lap 4-5	0.4 (± 1.2)	2.8 (± 0.4)	< 0.001*
Δ lap 5-6	-0.08 (± 0.6)	1.4 (± 0.2)	< 0.001*
Δ lap 6-7	0.6 (± 1.2)	3.0 (± 0.4)	< 0.001*
Δ lap 7-8	2.3 (± 0.8)	1.8 (± 0.4)	0.7 (± 0.9)

* SD smaller than 0.001 % due to the small mean change and corresponding Cl

Section: Original Investigation

Article Title: Influence of Pacing Manipulation on Performance of Juniors in Simulated 400 m Swim Competition

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Abstract

Purpose: To date, there is limited research examining the influence of pacing pattern (PP) on middle distance swimming performance. As such, the purpose of the present study was to examine the influence of PP manipulation on 400 m freestyle swimming performance. **Methods:** 15 front-crawl swimmers (5♀, 10♂, age: 18±2 y) performed three simulated 400 m swimming events. The initial trial was self-selected pacing (PP_{SS}). The following two trials were performed in a counter-balanced order and required participants to complete the first 100m slower (PP_{slow}: 4.5±2.2 %) or faster (PP_{fast}: 2.4±1.6%) than the self-paced trial. 50m split times were recorded during each trial. **Results:** Overall performance time was faster in PP_{SS} (275.0±15.9 s) compared with PP_{fast} (278.5±16.4 s, (p=0.05) but not significantly different to PP_{slow} (277.5±16.2 s, p=0.22). However, analysis for practical relevance revealed that pacing manipulation resulted in a ‘likely’ (> 88.2 %) decrease in performance compared with the PP_{SS}. **Conclusion:** Moderate manipulation of the starting speed during simulated 400 m freestyle races seems to affect overall performance. The observed results indicate that self-selected pacing is optimal in most individuals, yet it seems to fail in some swimmers. Hence future research should focus on the identification of those athletes possibly profiting from manipulations.

Key words: pacing template, simulated competitions, middle-distance, exercise

Introduction

The ability to appropriately distribute energy expenditure throughout an exercise task is extremely important to athletic performance.[1, 2] Recently published data from both simulated and actual competition indicates that in events of a similar distance, athletes have a relatively stable pacing template, irrespective of race tactics.[3-5] In this regard, it is widely believed that prior experiences have a major influence on self-selected pacing strategies.[1, 6] However, it is currently not well know whether such self-selected strategies result in maximal or optimal exercise performance.

In an attempt to optimise exercise performance, a number of studies have examined the influence of pacing manipulation on exercise performance with conflicting results.[7, 8] For instance, Foster et al.[9] controlled the first 1 km of a 2 km cycle time trial and observed that the even-paced trial produced the fastest overall time.[9] However, in a follow-up study, the same authors studied the 1.500 m speed skating event and reported that the faster the athletes started, the better the overall performance.[2] In addition,Gosztyla et al.[10] described that an even-pace strategy produced the slowest 5 km running performance in comparison to two different fast-start strategies (3 and 6 % faster in the first 1.6 km).[10] It has been suggested that a “fast-start” pacing might accelerate VO_2 kinetics at the onset of exercise and thus be responsible for the improved performance observed during short duration (3-6 min) cycling[11, 12] and rowing[13] events. Despite this, Thompson et al.[8] observed a decrease in 200 m breaststroke swimming performance when participants started 2 % above the average swimming speed, which was believed to be associated with the early development of muscular fatigue.[8] Furthermore, Mattern et al.[7] showed that reducing power output at commencement of a 20 km cycling time trial resulted in better overall performance when compared with an evenly-paced or fast-start trial. Yet compared to the aforementioned studies the start manipulations in this study were very high (± 15 %) which might have resulted in unrealistic pace changes. These confounding results between studies demonstrate that pacing strategies may be dependent on the modality of the event.

The impact of manipulating starting strategy on race performance is therefore equivocal, however a number of studies have demonstrated a positive effect of fast-start pacing on short-middle distance (2-5 min) exercise performance as measured through time-to-exhaustion or fixed duration laboratory tests.[12, 14, 15] However, to date there is limited data on the impact of manipulations in starting strategy on actual race performanceTo date, the majority of studies that have examined the influence of pacing manipulation on performance have been conducted in the laboratory, used a fixed duration[12, 14] rather then fixed distance or imposed changes by controlling power output rather than split times,[13] which is less comparable to athlete controlled changes in pacing during competitions. Clearly, further research is warranted in order to understand the influence of starting strategy on short-middle distance exercise performance, especially in actual race scenarios. Furthermore, the rapid acceleration resulting from diving,[1] along with the high resistive forces experienced during swimming may alter the influence of starting strategy has on performance[2], especially when compared with the current research typically conducted in cycling. As swimming velocity increases, frontal water resistance increases disproportionately.[2] While this also occurs in cycling the considerably greater resistance in swimming may result in a greater energy cost resulting from relatively minor fluctuations in velocity.[2, 16] In addition, stroke characteristics are influenced by velocity changes, leading to changes in swimming economy and energy expenditure.[17] Hence, the aim of the present study was to manipulate the initial section during 400 m front-crawl simulated competitions, in contrast to a self-selected race to analyse possible effects on overall performance as well as on the pacing pattern during later sections.

Methodology

Participants

A total of fifteen competitive front-crawl swimmers (5 females, 10 males, age: 14 to 23 y) volunteered for this study. The study was undertaken in accordance with the Declaration of Helsinki and approved by the appropriate ethics committee prior to commencement (Ärztekammer des Saarlandes, Saarbrücken, Germany). Prior to testing, all participants gave written informed consent and provided details on their training/racing history. If participants were under 18 years old, written informed consent was also obtained from their parents. Eight swimmers were recruited from the swimming squad at the local Olympic Training Centre (Rheinland-Pfalz/Saarland, Germany), seven from a swimming club ("Limmat Sharks" Zurich, Switzerland). Prior to the study, all swimmers completed a health history questionnaire to exclude those with any potential risk factors. Participants had a minimum of four years training and competition experience at or higher than a national level. Subject characteristics are given in table 1.

Design

Participants performed three experimental trials within a maximum three week period, separated by a minimum of 48 h. Since all participants had experience competing in 400 m front-crawl a practice trial was not performed. During each experimental trial participants completed a 400 m swim using front-crawl in a 50 m indoor swimming pool (26°C). During the first test participants were free to self-select their pacing pattern (PP_{SS}) throughout the entire 400 m. In the following visits participants were required to complete the first 25% of the event (100 m) using a fast- (PP_{fast}) or slow-start (PP_{slow}) strategy (described below). The PP_{fast} and PP_{slow} were conducted in a randomised order. According to recently published findings on the variability of pacing pattern in junior swimmers (CV: 1.0 % for the first 100 m in a 400 m race[4]) a manipulation of > 1% appears necessary to ensure a notable change in pacing. To provoke marked differences between conditions a manipulation of twice the upper 90% confidence limit of the variability (1.5%[4]) was used within the present study, leading to estimated changes of +3 % for PP_{slow} and -3% for $PP_{fast.}$.

To minimise diurnal variations all tests were conducted at the same time of the day. Participants recorded their activity and nutrition before the first trial and were asked to replicate it for the remaining tests. Participants were advised to maintain and record their training intensity and volume over the span of the study. They were also instructed to treat each race like a real competition and to refrain from strenuous exercise two days prior to each test. Females completed the tests in normal swimsuits, males were allowed to wear trunks up to the knees (according to FINA Swimming Rules, 2010).

Simulated competitions

Prior to each test, swimmers performed an individual warm-up which consisted of low- to moderate-intensity aerobic swimming (~1000m). The swimmers were advised to repeat the same warm-up before each trial. Prior to the manipulated trials participants also performed two externally paced 50 m repetitions with 30 s recovery in order to familiarise with the pacing intervention. Following the warm-up, each participant were given 20-30 min to prepare for the 400 m trial. During the PP_{SS} trials, athletes were required to complete the 400 m in the shortest possible time. During the PP_{fast} and PP_{slow} trials participants attempted to complete the first 100 m at 3% faster or slower than the first 100 m in PP_{ss} trial, respectively. Swimming velocities during the first 100 m in the manipulated trials were controlled either by a flashing light system (GTC, Ludwigshafen, Germany) installed at the bottom of the pool (Saarbrücken, Germany) or by acoustic signals every 25 m (Zurich, Switzerland). Subjects were instructed to complete the remaining distance after the manipulated section in the shortest possible time.

Due to the rapid acceleration caused by diving, swimmers typically complete the first 50 m of 400 m events faster than any other section of the race.[16] The pace of the first 100 m was therefore set as two slightly different 50 m split times, based on the PP_{SS} trial. To analyse the influence of the manipulations on pacing pattern without the start dive, a camera recorded the time taken to reach 15 m. The measurement of start time began with the start signal and ended when the swimmer's head touched the digital line superimposed onto the videotape at 15 m from the start. During each event overall time and 50 m split times were measured using handheld stop-watches. The same investigator measured times for the same swimmer during each trial. Split times were measured during the turn when swimmers touched the wall with their feet and final times when participant touched the wall with their hand. Stroke rate was determined in the middle of each 50 m lap by measuring the time taken to complete three strokes. Capillary whole-blood samples (20 µl) were taken from the hyperemized earlobe immediately, 1, 3, 5 and 7 min after exercise and analyzed for blood lactate concentration (automated enzymatic-amperometric method, Greiner BioChemica, Flacht, Germany). Heart rate (Polar Electro, Kempele, Finnland) was measured ~10 s after cessation of each test.

Statistical analysis

Data are presented as means and standard deviations (SD). A one-way repeated measures ANOVA was performed to examine differences between final times. In order to compare pacing, velocity in all trials was expressed relative to average race velocity (normalised mean velocity). This approach of expressing pacing as the difference between current and overall mean velocity is well accepted.[1] A two-way ANOVA was used to compare stroke rate and pacing (normalised velocity) between trials (with and without start dive). Where significant effects were observed, a Scheffé post-hoc test was performed. $p < 0.05$ was accepted as significance for statistical comparisons.

Magnitude based inferences were also conducted in order to determine the smallest worthwhile differences in overall performances between trials[18]. This approach represents a contemporary method of data analysis that uses confidence intervals in order to calculate the probability that a difference is practically beneficial, trivial or harmful. The smallest worthwhile difference for 400 m front-crawl performance was set as 0.3 of the typical variation in an athletes performance (1.3 %[5, 19]) Where the chance of benefit and harm were both calculated a qualitative descriptor was assigned to the following quantitative chances of performance effect: 0.5-5%: very unlikely; 5-25%: unlikely; 25-75%: possibly; 75-95% likely; 95-99.5%: very likely; >99.5%: most likely.[18] Cohens´s *d* effect sizes and thresholds (0.2, 0.6, 1.2, 2.0, 4.0 for trivial, small, moderate, large, very large and extremely large[18]) were also used to compare the magnitude of the differences in overall performance time.

Results

Performance times

By design, participants completed the first 100 m of the PP_{slow} 4.5 ± 2.2 % (2.9 ± 1.5 s) slower and the first 100 m of the PP_{fast} 2.4 ± 1.6 % (1.6 ± 1.0 s) faster than the PP_{ss}. A significant main effect for overall performance time was observed between trials ($p = 0.04$). Post hoc analysis revealed a significant difference between PP_{SS} and PP_{fast} ($p = 0.05$) but not PP_{slow} ($p = 0.20$; table 2). Analysis of magnitude-based differences showed that both PP_{slow} and PP_{fast} were likely to very likely to result in slower performances when compared with PP_{SS} (table 2). However, seven of the 15 subjects recorded their fastest time during a manipulated race (3 in PP_{fast}, 4 in PP_{slow}). On average swimmers were 0.6 % (min: 0.1 %; max: 1.4 %) faster compared to PP_{SS}. Mean and individual times to completion are shown in figure 1.

Pacing pattern

Normalised pacing pattern for all three conditions with and without the dive start are shown in figure 2. A significant interaction effect was observed between conditions both with and without the dive start ($p < 0.001$). Post hoc analysis revealed that pacing was different between conditions during the first 100 m ($p < 0.001$), with no further significant difference between conditions ($p = 0.45$; figure 2). When including the dive start in the analysis the first 50 m of the race was significantly faster than remaining sections in all trials ($p < 0.001$). However, when accounting for the 15 m dive start an even pacing pattern was observed in PP_{SS} with no differences between sections over the whole trial ($p > 0.21$; figure 1). In PP_{fast} the initial 100 m was still significantly faster than all other sections of the trial ($p < 0.001$), and the last 50 m in PP_{slow} was faster in comparison to the first 50 m ($p = 0.02$). Figure 3 additionally displays the individual pacing patterns of the seven swimmers showing better performances in a manipulated race compared to those showing best results in PP_{SS}.

Blood lactate, heart rate and stroke rate

BLa_{final} ($p = 0.33$) and HR_{final} ($p = 0.47$) were not significantly different between conditions (table 2). Stroke rate (figure 4) showed a significant global interaction effect between trials ($p < 0.001$). However, post hoc analysis only detected a significantly lower stroke rate in the third section compared the first 50 m in PP_{fast} ($p = 0.02$). No significant difference in stroke rate could be observed within PP_{slow} and PP_{SS} ($p > 0.26$).

Discussion

The purpose of the present study was to examine the influence of pacing manipulation on performance during middle-distance swimming. The main finding was that manipulation during the initial 25 % of a 400 m front-crawl swimming event reduces overall performance in well-trained swimmers. Compared with a self-paced trial, the fast start (PP_{fast}) and slow start (PP_{slow}) strategies reduced overall performance time by more than 2.5 s. Considering the low variability (< 2 %) in performance of well-trained swimmers these differences appear relevant to high-performance sport.[4, 5] This assumption is supported by the analysis of magnitude-based differences indicating that both pacing manipulations in this study were ′likely′ to ′very likely′ to be detrimental to performance when compared with the self-paced trial. However, since nearly 50 % of the participants (7 out of 15) recorded their fastest time during a manipulated trial, this study all indicates that some swimmers may fail to self-select an optimal start strategy when performing a 400 m front-crawl race. On average these swimmers were 0.6 % faster. Based on recently published findings,[4, 5] the smallest substantial change in swimming performance was assumed to be a reduction or increase in time of more than 0.39 %, therefore the observed enhancements in performance appear relevant for real competitions.

It has previously been found that the adoption of a fast start at commencement of middle distance events may improve performance over slow- or even-start pacing strategies.[20] Indeed, a relatively fast start pacing strategy has been shown to improve high-intensity cycling performance during task of a very similar duration to the present study (~4.6 min).[21] However, within the present study increasing speed at commencement of the PP_{fast} trial by 2.4 %, over that of the self-paced trial, resulted in significantly slower overall performance times. Differences in the effectiveness of a fast start pacing strategy on performance between this and previous studies[12, 13] is likely to be due to differences in the exercise mode (swimming vs cycling and rowing) and methods of pacing manipulation. The dive start in swimming allows athletes to rapidly accelerate to race speed and as a consequence a fast start pacing strategy is typically adopted during self-paced 400 m swimming (figure 1).[16] Indeed, when removing the dive start from the beginning of the self-paced trial (PP_{ss}), athletes in the present study adopted a much more even pacing strategy (figure 1). However, the majority of pacing research examining middle-distance performance has to date been conducted within sports such as cycling[11, 12, 14] and rowing,[13] whereby athletes are required to accelerate from a standing start. During these events increasing energy expenditure at the beginning of the event in order to minimise the time spent at low velocities can have a meaningful effect on performance.[1, 22] This time saving hypothesis is based on the principle that increasing intensity in order to overcome a period of high external resistance (i.e. acceleration, head-winds or head-currents) and reducing intensity when external resistance is low (i.e. when momentum is high, tail-winds or tail-currents) assists in maintaining a more even overall velocity and thus faster performance times.[11, 21, 23] Consequently, the rapid acceleration resulting from a dive start may reduce the effectiveness of a fast-start pacing strategy on swim performance.

Previous research has speculated that in middle distance events a fast start strategy might lead to better performances. Suggested reasons are a speeding of O_2 kinetics, leading to a greater oxidative contribution to the race and thereby sparing the anaerobic reserve until the end of the race.[11, 15] It therefore could be expected that the relatively fast start pacing strategy used in the present study would have improved VO_2 on-kinetics and thus improved performance beyond that of the more evenly paced slow-start trial. However, within swimming athletes are required to overcome significant fluid resistance in order to produce forward motion and since the relationship between power output and velocity is not linear, greater energy expenditure is required to exercise at faster speeds. Therefore, in order to increase velocity, and adopt a fast start in the present study, athletes were required to dramatically increase their energy expenditure, which may have led to an early and accelerated rate of fatigue during the exercise bout. Indeed, the majority of studies that have observed a benefit of a fast-start pacing strategy during middle-distance events have been conducted in laboratory settings,[11, 12] whereby the association between energy expenditure/power output and velocity may inaccurately represent relationship observed during actual competition. To the authors´ knowledge, this is the first study assessing the effects of pacing manipulations in actual race performance. Clearly, further field-based research similar is warranted in order to better understand if any possible benefit of a fast start pacing strategy to oxygen kinetics is negated by an increase fatigue resulting from the higher resistive forces experienced at faster speeds.

Furthermore, it might be possible that the fast-start pacing strategy resulted in changes in swimming mechanics leading to a reduction in economy (e.g. significantly higher stroke rate in the first 100 m; figure 3). Even though speed was only slightly altered, the change in swimming technique to achieve this small increase might have been detrimental. Swimming velocity is the product of stroke rate and stroke length,[17] and both factors need to be considered when optimising performance.[24] However, it has been concluded that stroke length is the most critical factor in achieving best performance.[25] In this regard, it has been assumed that the swimmer who moves the greatest distance per stroke has the most effective swimming technique.[17] In the current study an increasing stroke rate in PP_{fast} might have led to a decrease in stroke length and stroke depth, hence, reducing the biomechanical momentum of the propulsive muscle, and decreases the potential for propulsion.[24] Ultimately, this reduction in economy leads to higher energy expenditure and thus an earlier development of fatigue. Similarly Hettinga et al.[26] recently observed that a fast start strategy does not lead to a better performance in a 1.500 m speed skating race, even though a theoretical model predicted this to be optimal. The authors also speculated that the fast start lead to changes in technique resulting in mechanically inefficient skating.[26]

Due to the rapid acceleration resulting from the dive start in swimming it is plausible that commencing middle-distance swimming events at a slightly slower velocity may be beneficial to performance. However, within the present study it was found that commencing the trial with a relatively slow speed (PP_{slow}) resulted in significantly slower performance times in comparison to the self-paced trial (PP_{SS}). It is plausible that the 2.5 to 4.5 % change in pacing induced in the present study was insufficient to result in substantial disturbances in metabolism over the duration of the entire trial. Supporting this, average heart rate and blood lactate upon completion were not significantly different between trials in the present study. Similarly. Thompson et al.[8] did not observe significant differences in blood lactate, VO_2, and perceived exertion between self-paced, even paced and slow-start pacing in 200 m breaststroke swimming.

The reduction in performance observed in both the manipulated pacing trials of the present study may also be associated with prior learning or experience, demonstrated in several studies.[6, 27-29] The pacing pattern during time trials appears to follow a predetermined template associated with prior experience, which is modified by a variety of sensory feedback mechanisms.[6] In this regard, Mauger et al.[16] recently described how a fast-start even-pacing strategy is most commonly chosen in 400 m freestyle competition. Hence, it can be considered that PP_{slow} does not represent the usual pacing pattern of competitive swimmers, and PP_{slow} might be equally "disturbing" for the swimmers as PP_{fast}.

Interestingly however, seven of the 15 swimmers in the present study demonstrated their best performance in one of the manipulated races. These data indicate that the self-selected pacing strategy for these athletes was not optimal. As four of these athletes benefited from the PP_{slow} while three others benefited from the PP_{fast}. These results indicate that the influence of pacing manipulation on performance appears variable and athletes may benefit from practicing numerous strategies during training in order to maximise performance. Thomas et al.[20] recently showed that despite the common assumption that an even-pacing strategy is best in endurance events lasting > 4 min, nine out of 15 cyclists were not able to finish a 20 km cycling time trial, when forcing to perform an even-pacing. Hence, the authors concluded that a self-selected parabolic shaped pattern results in less cumulative stress. This might especially be true for swimming events, given that the dive start allows athletes to rapidly accelerate. Indeed the swimmers who optimised their race performance in this study also adopted a more parabolic shaped pacing pattern in the manipulated races (figure 4). Furthermore, the four swimmers showing better results whilst starting slower (PP_{slow}) where able to perform a greater end spurt compared to their self-selected pattern leading to a more parabolic-shaped pattern. In this regard it is further remarkable that on average the end-spurt was similar in all three conditions with the last 50 m being 2.7 % (PP_{slow}) to 3.4 % (PP_{SS}) faster than the previous laps. Although it may be expected that the slow start strategy in PP_{slow} would enable swimmers to save energy stores therefore resulting in the greatest increase in speed at the finish, PP_{SS} showed the largest increase in velocity at the end of the race (3.4%). Tucker[30] proposed that the occurrence of a end-spurt indicates that the distribution of pace selected during self-paced exercise is centrally regulated in accordance to an "anticipatory-feedback model". Therefore, it might be assumed that swimming velocity was continuously attenuated until the final 50 m, possibly in response to changing afferent signals, to save energy stores and to avoid catastrophic failure until the end of the race.[28, 31]

Study limitations

Swimmers raced against each other in the self-paced trial, whereas participants had to swim alone in the manipulation trial. The race situation in the self-selected trial was chosen to resemble competition and competition pacing as close as possible. Since bLa, HR and RPE values were not different between $PP_{fast/slow}$ and PP_{SS} it can be assumed, that athletes finished the races as fast as possible. Additionally approximately 50% of the participants were faster in a manipulated race indicating that athletes performed these events maximally.

The absolute and relative manipulations of the first 100 m section were slightly different between PP_{slow} and PP_{fast}. In our pilot work equal changes in pace for PP_{fast} and PP_{slow} were carried out, however, athletes were not able to pace such high velocities precisely mainly due to the start dive acceleration. Therefore, the recently published CV[4] of the first 100 m during a 400 m front-crawl race was chosen as the minimum deviation from PP_{SS}. Subjects had to swim alone in the manipulated trials, due to the differences in the initial 100 m section. It can be speculated, that racing against an opponent might have led to better performance times in PP_{SS} compared to the manipulated trials.[16] However, recently published data on reliability of competition pacing showed stable patterns and overall performance times independent of different competitors.[5]

Most available studies on pacing manipulation measured gas exchange values and/or metabolic markers (e.g. blood lactate over the whole trial).[7, 28] Gas analysis during swimming in a pool is associated with methodical difficulties which can interfere with swimming technique. Body position and drag might be influenced by using spiroergometric equipment. In addition, flip turns and gliding is impossible. This likely affects swimming economy and hence possibly leads to invalid results. Furthermore, pacing is affected as well and results are hardly transferable into training and competition routine. However, for future research on pacing pattern in swimming physiological mechanisms might be an interesting topic.

Conclusions and Practical Applications

Results of this study indicate that a moderate manipulation of the starting speed during simulated 400 m freestyle races affect overall performance. It additionally appears that some swimmers may not have self-selected an optimal strategy, since performance was better in a manipulated race. Well-trained swimmers could therefore benefit from trying and practicing "new" pacing strategies during training or even real competition. Further research should focus on the identification of those athletes possibly profiting from pacing manipulations.

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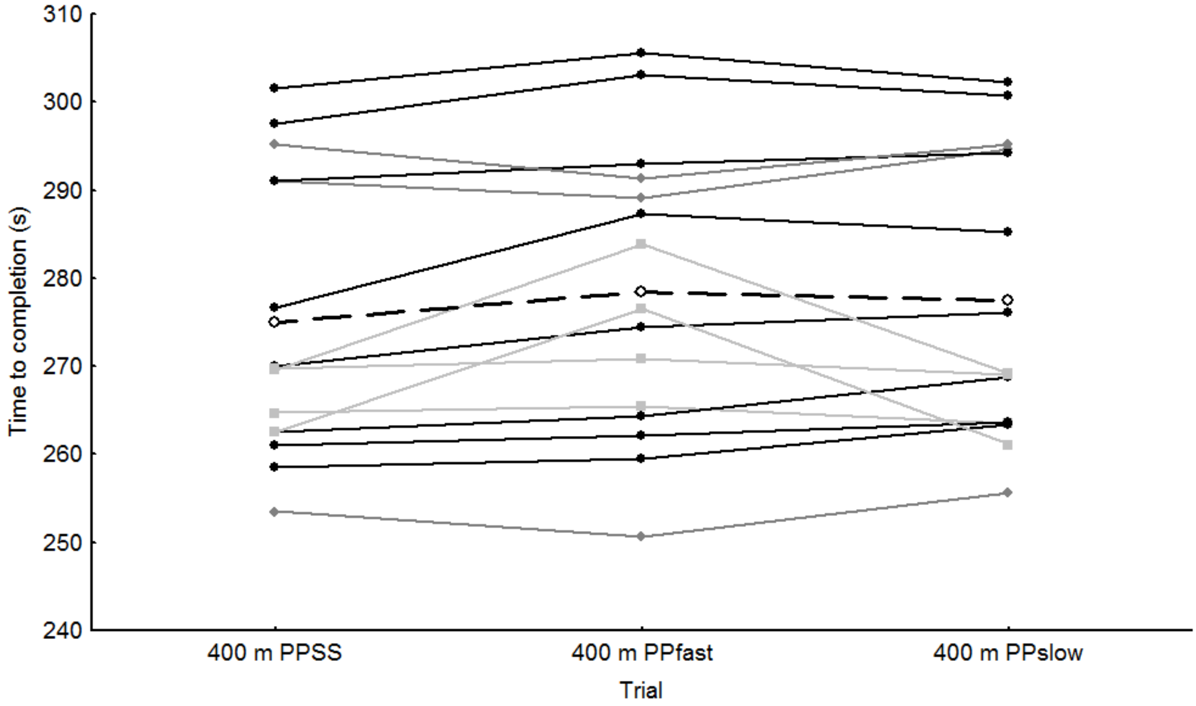

Figure 1: Mean (black line) and individual differences in time to complete the 400 m swimming trial (black line: best performance in PP$_{SS;}$ light grey: best performance in PP$_{slow}$; dark grey best performance in PP$_{slow}$).

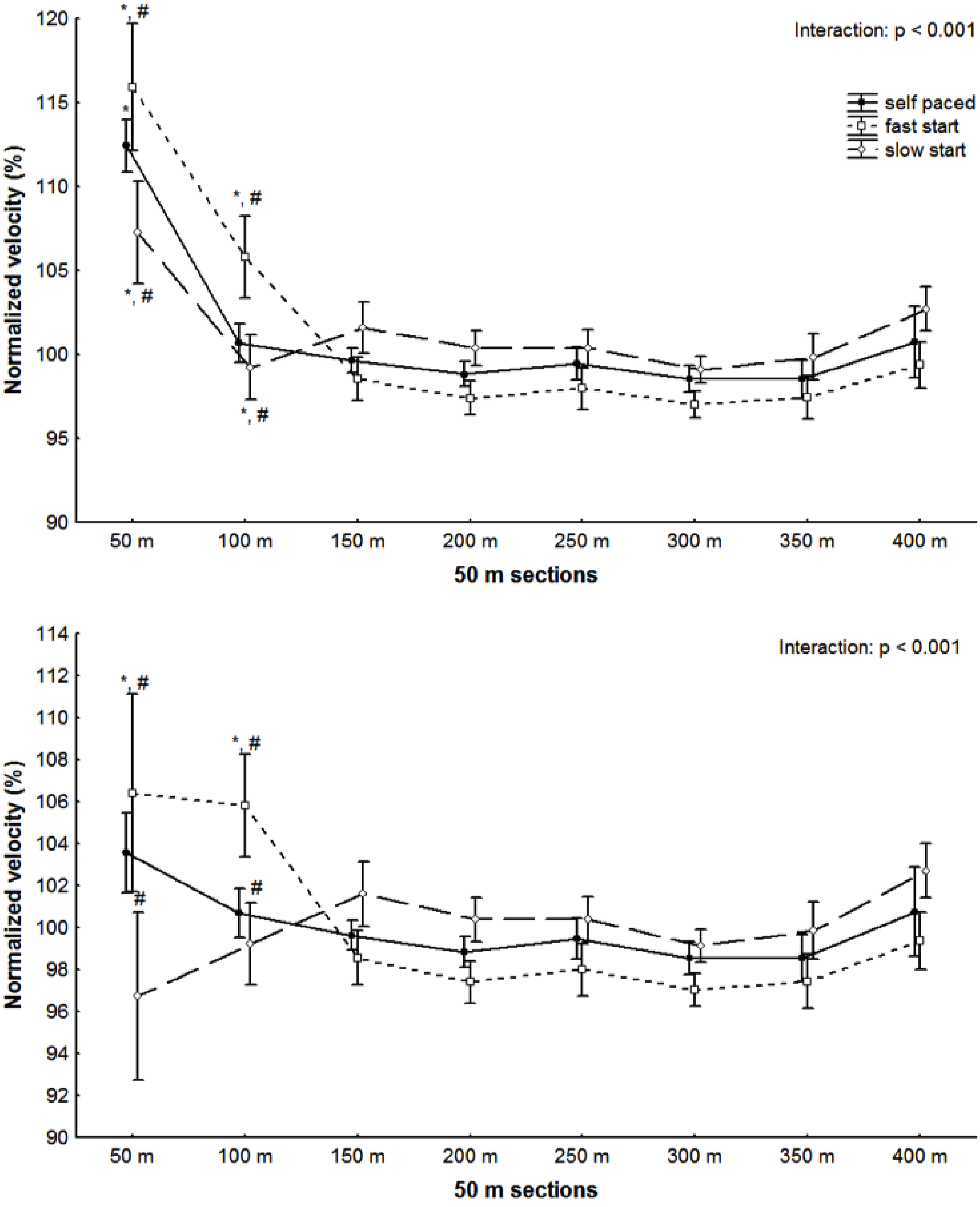

Figure 2: Normalized pacing pattern during the self-paced (solid lines), fast-start (dotted lines) and slow-start (dashed lines) 400 m trials; with (upper graph) and without (lower graph) start dive (15 m start time) (* = significantly different to all other sections in that race; # = significantly different to the corresponding section in PP_{SS}).

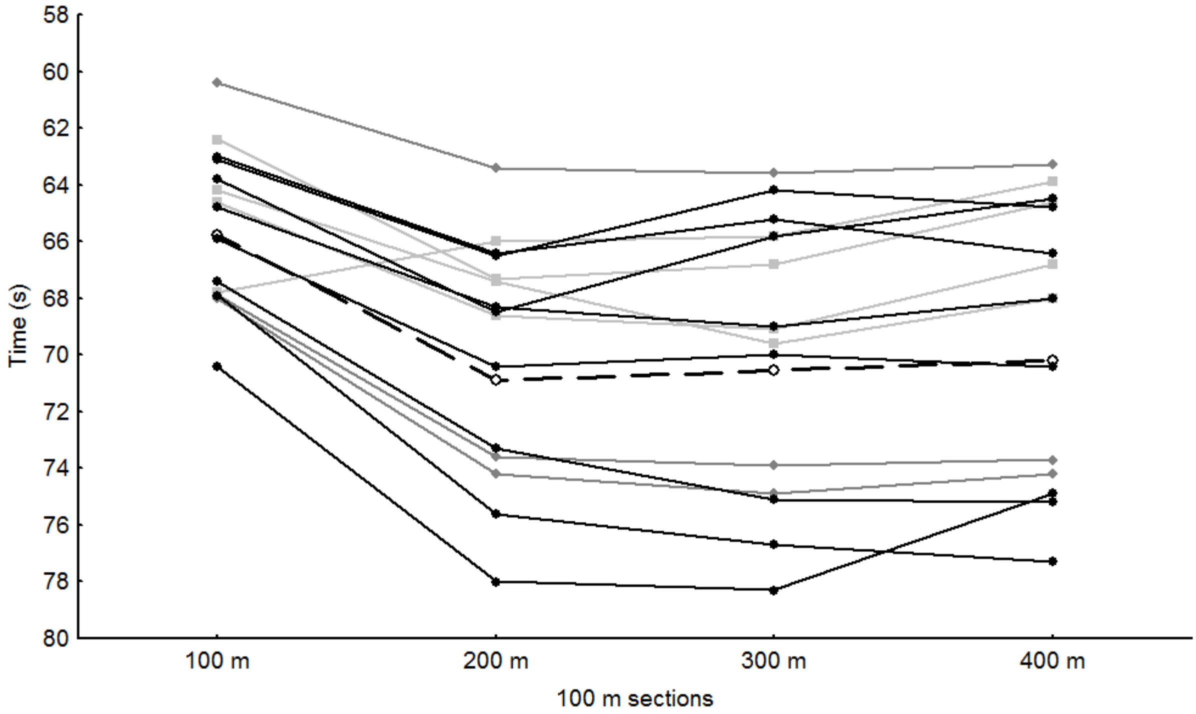

Figure 3: Individual pacing patterns in the best 400 m trial of each athlete (black line: best performance in PP_{SS}; light grey: best performance in PP_{slow}; dark grey best performance in PP_{slow})

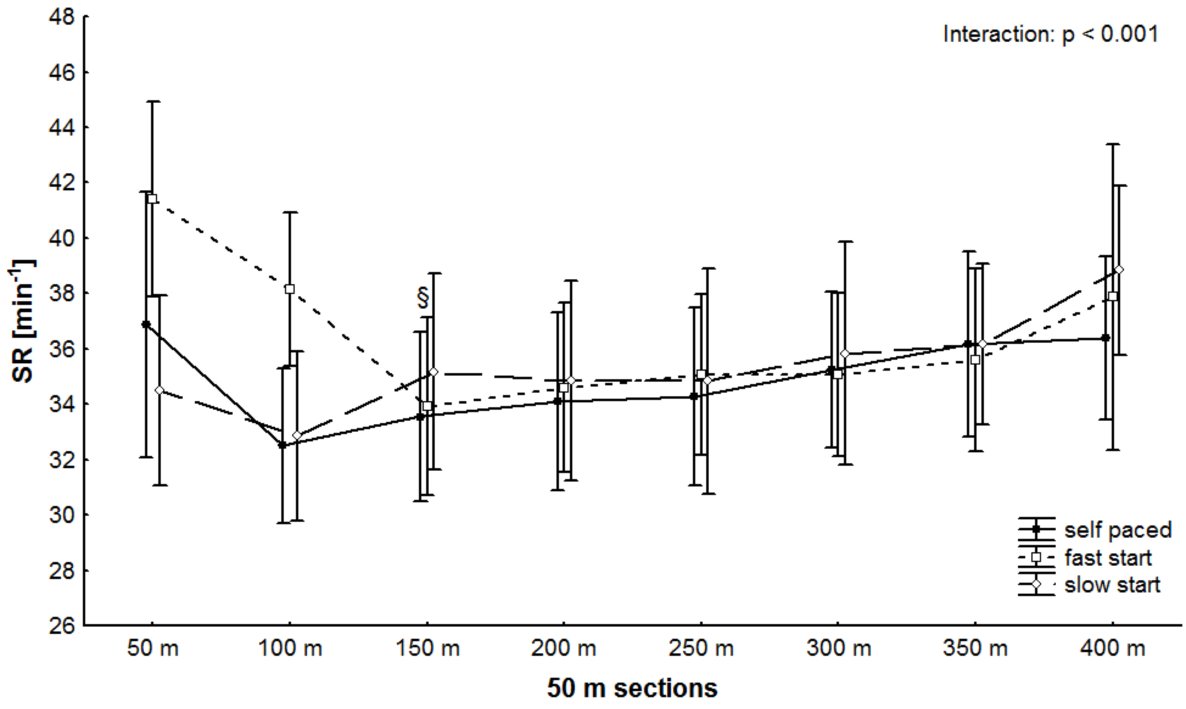

Figure 4: Stroke rate pattern during the self-paced (solid lines), fast-start (dotted lines) and slow-start (dashed lines) 400 m trials (§ = significantly different compared to the first section in that race).

Table 1: Anthropometric data for all participants. Data as mean ± standard deviation.

	Age (years)	**Height (cm)**	**Weight (kg)**	**Training history (years)**	**Training amount (km*week^{-1})**	**100 m time (min)**
male participants (n = 10)	19.2 ± 2.0	182.4 ± 10	75.9 ± 9.1	8.6 ± 2.3	32.9 ± 8.6	0:57.4 ± 0:02.2
female participants (n = 5)	16.2 ± 1.8	175.8 ± 0.9	65.5 ± 7.6	4.5 ± 0.6	31.8 ± 3.9	1:04.9 ± 0:01.1

Table 2: Overall results for the 400 m self-paced (PP_{ss}), fast- (PP_{fast}) and slow- (PP_{slow}) start trial as well as Coehn´s effect sizes and changes of competition relevance. (Data as mean ± standard deviation, 95% confidence limits for mean difference between trials).

Test (n = 15)	**400 m (PP_{SS})**	**400 m (PP_{fast})**	**400 m (PP_{slow})**
Overall performance time (min)	4:35.0 ± 0:15.9	4:38.5 ± 0:16.4*	4:37.5 ± 0:16.1
d		0.21	0.15
Mean difference to PP_{SS} (sec)		3.5 ± 5.4	2.5 ± 2.9
Probability of practical relevance		very likely (96.2%)	likely (86.1%)
bLa_{final} ($mmol \cdot L^{-1}$)	10.7 ± 2.4	10.4 ± 2.3	9.8 ± 3.5
HR_{final} (bpm)	178 ± 9	179 ± 8	176 ± 11
SR (min^{-1})	36.8 ± 4.5	37.2 ± 3.8	36.6 ± 3.4

*significantly different to PP_{SS} ($p < 0.05$); bLa: blood lactate concentration, HR: heart rate, SR: stroke rate